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Geospatial Characterization of Fluvial Wood in a Midwestern, Semi-Confined Alluvial River System

Derek Joseph Martin
University of Tennessee - Knoxville, dmarti49@utk.edu

To the Graduate Council:

I am submitting herewith a dissertation written by Derek Joseph Martin entitled "Geospatial Characterization of Fluvial Wood in a Midwestern, Semi-Confined Alluvial River System." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Carol P. Harden, Major Professor

We have read this dissertation and recommend its acceptance:

Liem Tran, John Schwartz, Robert T. Pavlowsky

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Geospatial Characterization of Fluvial Wood in a Midwestern, Semi-Confined Alluvial River System

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DEDICATION

This dissertation is dedicated to my wife, Erin, for her unconditional love and support, and to my loving parents, who made this journey possible.

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ABSTRACT

Large woody debris (LWD) has become universally recognized as a key component of the ecological and geomorphological function of river systems. The use of LWD as a restoration tool in Midwestern river systems is widespread, yet LWD-related restoration strategies are primarily supported by research from the Pacific Northwest or other physiographically similar regions. The purpose of this dissertation research was to investigate the longitudinal arrangement patterns of LWD and to characterize LWD and its effects on sediment storage within the Big River, a Midwestern river system located in the Missouri Ozarks. I adopted a multi-scale approach to analyze (1) large-scale longitudinal patterns of LWD arrangement, (2) potential geomorphic and riparian control mechanisms of LWD arrangement, (3) reach-scale characteristics of LWD, and (4) reach-scale relationships between LWD and sediment storage.

The results of this research demonstrate that the longitudinal arrangement of LWD along the Big River is not random. Along many segments of the Big River, LWD density is spatially periodic. Periodicity showed a strong positive association with gravel bar spacing and meander wavelength, although there were insufficient data to statistically confirm the relationship. Furthermore, reaches that exhibited strong periodicity yielded stronger relationships between LWD density and the geomorphic/riparian independent variables tested. Analyses consistently identified valley width and sinuosity as being associated with LWD density.

Wood loads in the Big River were low relative to those in streams located in the commonly studied Pacific Northwest, and high relative to other low- to mid- gradient river systems. In general, wood piece size was large relative to those of other river systems, and may suggest, along with field observations, that bank erosion is the dominant wood recruitment mechanism. Furthermore, the contribution of LWD to reach-scale sediment storage was low relative to other in-channel sediment stores.

These results provide a baseline characterization of LWD for a semi-confined-meandering river system. This will help provide a directive for LWD-related management in stream restoration ventures in semi-confined meandering river systems and provide a first step toward developing more accurate models of LWD dynamics.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1. Purpose

The purpose of this dissertation is to investigate the broad-scale geomorphic controls on the arrangement of large woody debris (LWD) within the Big River of East Missouri and provide a baseline characterization of LWD within a semi-confined, Midwestern river system. Information generated by this dissertation is intended to provide guidance to those who incorporate LWD in river management and rehabilitation strategies, particularly in the Midwest, where fluvial wood processes are least understood, compared to other regions of the U.S. Additionally, this dissertation highlights the application and effectiveness of geospatial techniques as applied to the longitudinal analysis of river systems.

Large woody debris, also referred to as fluvial wood, has been identified as a key factor affecting river system functionality. Research in the fields of fluvial geomorphology and landscape ecology has contributed significantly to the growing literature on this subject and has revealed a universal recognition of the importance of LWD to the ecology and management of world rivers, as well as a universal consideration of LWD as an integral part of conservation and restoration efforts (Gregory et al., 2003). In particular, LWD is known to affect sediment transport rates by creating temporary to long-term sediment sinks. The role of LWD in sediment dynamics, while already known to be significant in particular fluvial systems, is likely to increase in those and in other systems as riparian forest conservation efforts grow, allowing riparian trees to mature, and as climate change continues to alter mid-continent precipitation patterns, potentially altering river system sediment yields and increasing the ability of rivers to transport wood. With fine "clean" sediment currently listed as the number one pollutant in the nation's rivers (EPA, 2009), it is imperative that we understand the recruitment and transport processes of LWD and the geomorphic significance of LWD in order to better manage forested river channels. This dissertation research was undertaken to increase our understanding of LWD dynamics and the influence of LWD on fluvial geomorphic processes by providing a new perspective and by implementing novel approaches. Because it takes place in a physical setting not accounted for in the LWD literature, it should help improve our theoretical understanding of LWD dynamics.

This research is important for the following reasons: (1) LWD is an integral component of fluvial systems; (2) Stream restoration projects increasingly include the addition of LWD to the channel; (3) LWD dynamics are poorly understood in Midwestern river systems; (4) Wood loads are likely to increase in Midwestern river systems as successional riparian forests age; and (5) The role of LWD in fluvial sediment dynamics is poorly understood, particularly in lower to medium gradient, alluvial rivers. This work is also intended to contribute to our understanding of sediment storage characteristics of a system containing large volumes of lead-contaminated sediments. It is designed to contribute to our understanding of trans-scale fluvial processes.

1.2. Fluvial Wood

In the context of river systems research, large woody debris (LWD) can be defined as any wood occurring within the bankfull channel that is greater than 0.1 m in diameter and greater than 1 m in length (Fetherston et al., 1995). The effects of LWD on river systems have emerged as a popular research topic in the past two decades (Gregory et al., 2003), not only for fluvial geomorphologists, but also for ecologists, geomorphologists, and hydrologists. The combined efforts of this research pool have made it quite clear that LWD can be a significant factor affecting the functionality, particularly the geomorphic functionality, of river systems (Keller, 1979; Bisson et al., 1987; Shields, 1992; Smith et al., 1993). Large woody debris can form pools, create waterfalls, and produce a diversity of habitats for aquatic biota. Additionally, LWD can alter channel form (Keller and Swanson, 1979; Keller and Tally, 1979) and regulate the transport of sediment (Bisson et al., 1987) by creating in-channel depositional zones such as obstruction pools and mid-channel bars. Widespread recognition of the role of LWD in the ecological and geomorphological function of river systems has made it an important factor in stream restoration design (Reich et al., 2003) and river management strategies (Abbe et al., 2003) in many regions.

1.3. Dynamics of Fluvial Wood

The relationships between LWD and the physical characteristics of river systems vary substantially with changes in land use and riparian tree species, climatic and hydrological regime, geomorphological setting, and the watershed management context (Gurnell et al., 2002). These relationships ultimately control the recruitment, transport, and deposition of LWD along and within a river system.

LWD is recruited to the stream channel through a variety of different mechanisms. A majority of studies conducted on LWD recruitment have identified mortality of riparian trees as the primary source of LWD recruitment, in addition to bank erosion, fire, mass wasting events, and other mechanisms (Benda et al., 2003). Processes of recruitment vary substantially by region in relation to dominant weather patterns, topography, and the age of the riparian forest. For example, most LWD research has been conducted in the Pacific Northwest region of North America, where many forests contain old-growth stands and thus have a higher probability of tree mortality; and where steeper slopes, combined with high levels of precipitation, induce frequent mass wasting events. Benda et al. (2003) recognized the importance of identifying regional differences in wood recruitment processes, especially for the purpose of riparian management. Wood recruitment processes ultimately affect the amount of LWD in the channel and, subsequently, the longitudinal arrangement of LWD along the channel.

In general, previous field research has shown that the amount of LWD in studied fluvial systems decreases in the downstream direction as high input rates, combined with low transport capacity in low-order reaches, grade to low input rates with high transport capacity in high-order reaches (Swanson, 2003). However, the characteristics of transport and the subsequent deposition of LWD along the river network vary substantially as a result of variations in wood size, wood availability, and the transport ability of the stream (Swanson, 2003).

In general, LWD already in the channel is more likely to accumulate in situations where it comes in contact with the bank or bed (Nakamura and Swanson, 1994). Wide, sinuous reaches, where the channel curvature is likely to force LWD along an outside bend or onto alternate bars, are more prone to LWD accumulation than straight, narrow reaches with high shear stresses and no bar development. Some research from other regions has shown that channel width and sinuosity are the primary factors that control the abundance and distribution of LWD. Nakamura and Swanson (1994) suggested that wide channels bordered by floodplains and terraces possess abundant LWD storage sites and that sinuous reaches tend to form secondary channels along valley walls that trap LWD during high flows. Tributary junctions may also be significant LWD storage sites (Nakamura and Swanson, 1994; Swanson and Lienkaemper, 1979). Additionally, Braudrick and Grant (2001) performed a flume study in which they determined that the distance traveled by LWD is significantly related to the ratios of the piece length to average channel width, and piece length to maximum radius of curvature of the channel. They also determined that large pieces can move farther than small pieces if the distribution of potential storage sites is infrequent, allowing the built up momentum of a moving piece of LWD to overcome channel roughness elements. The research mentioned above demonstrates the wide range of potential controls on fluvial wood distribution across a wide variety of system types, and thus demonstrates the inherent complexity in attempting to model such distributions. However, Swanson (2003) developed four typologies, or models, of wood arrangement based on the dominant control mechanisms described above. The four models are described below:

1. *Discrete-source-area control* – Arrangement of discrete source areas along a river dominates patterns of wood in the river where transport distances are much shorter than the spacing of source areas.

2. *Trapping-site control* – In systems with effective trapping sites, their arrangement dominates wood accumulation patterns where transport distances are long relative to spacing of source areas.

3. *Transport-control* – In river reaches lacking discrete wood-trapping sites and where transport distances are long relative to source-area spacing, wood is randomly distributed, regardless of the pattern of wood source areas and input processes.

4. *Dispersed-source-control* – In areas of dispersed input and very limited transport capacity, wood is randomly distributed and amounts reflect forest stand and decomposition histories.

Therefore, systems with discrete source areas and/or trapping sites should display arrangement patterns that reflect those source areas and/or trapping sites. Alternatively, systems with high transport capacity and non-discrete trapping sites, or low transport capacity and dispersed source areas, should display random patterns of arrangement.

1.4. Fluvial Wood and Sediment Dynamics

Following recruitment to the channel, LWD helps regulate the transport and storage of sediment by providing a low velocity environment that can induce sediment deposition. In many high gradient systems, sediment storage associated with LWD exceeds the annual sediment yield by more than 10-fold (Montgomery et al., 2003). Conversely, other researchers have shown that sediment storage associated with LWD in lower gradient systems is comparably less (Magiligan et al., 2008; Wohl, 2011). However, peer-reviewed literature on LWD-related sediment storage is biased toward mountainous systems by a ratio of nearly 10:1. Considering this regional bias, research has shown that the contribution of LWD to sediment storage decreases down the stream network (Lassettre and Harris, 2001). Bilby and Ward (1989) found that, in streams draining old growth forests of southwest Washington, 40% of LWD pieces were associated with sediment deposition in channels that were <7 m wide. Continuing down the stream network, this percentage decreased to less than 20% when the channel exceeded 10 m in width. However, Magilligan et al. (2008) found that LWD has less effect on sediment storage in smaller streams compared to larger streams in coastal watersheds of Maine. This lack of agreement highlights one of the discrepancies between high gradient, mountainous systems and other low-gradient systems.

In many cases, the effect of LWD on sediment storage and mobility has been studied by evaluating the consequences of LWD removal. In general, studies in which LWD was removed showed an increase in particle mobility following removal (Assani and Petit, 1995). In a headwater stream in Montana, removal of an LWD jam resulted in bedload transport rates twice as high as those of the pre-removal condition (Bugosh and Custer, 1989). Likewise, in a study conducted by Smith et al. (1993), bedload transport was monitored in a southeastern Alaska gravel bed stream following the removal of all LWD from a 95-m reach. The result was a four-fold increase in bedload transport for the six months following removal. In addition, many studies have linked LWD to increases in the depth, size, frequency, and fine sediment retention of pools (Hogan, 1987; Gurnell and Sweet, 1998; Inoue and Nakano, 1998; Nakamoto, 1998).

In addition to sediment storage, LWD can also be responsible for sediment remobilization and, concomitantly, channel-form alteration. Research shows that the influence of LWD on channel form varies greatly, depending on the size of the channel, the gradient, the type of LWD, and a variety of other factors. That influence can be significant (Keller and Swnason, 1979). The presence of LWD has been linked to changes in channel form resulting from bank erosion and bank protection. Bank erosion occurs as a result of flow being redirected by the LWD toward the banks. Bank protection occurs as a result of flow being deflected away from the banks or being significantly slowed by LWD as it approaches the bank (Daniels and Rhoads, 2003). The former case is exemplified by a study in which Nakamura and Swanson (1993) measured channel widths at LWD locations in an Oregon stream and found that sites with LWD had channel widths 25% to 58% wider than sites without LWD. Additionally, LWD can exert significant force on the channel bed, depending on the location of the wood within the water column, the size of the LWD, its angular orientation relative to the flow, and the nature of the bed material (Mutz, 2003). These studies, and others, indicate that LWD may serve a significant role in the overall longitudinal connectivity of fluvial sediments through the regulation of sediment transport.

1.5. Fluvial Wood as a Management Tool

Large woody debris has probably been used as a stream management tool for at least 100 years (Needham, 1969, cited in Reich et al., 2003). It has been widely recognized that LWD increases the complexity of river systems, both hydrologically and geomorphologically (Keller and Swanson, 1979; Lienkaemper and Swanson, 1987, Abbe and Montgomery, 1996, 2003; Buffington and Montgomery, 1999; Brooks and Brierly, 2002) and as such, has become a widely popular component of stream restoration projects. In addition to our growing understanding of the functional role of LWD in river systems, LWD is also seen as a cost-effective and natural solution to river restoration goals (Reich et al., 2003). In most cases in which LWD was used for river system management, LWD was added to the river system as a structural element to improve fish habitat (Seehorn, 1992; Hunt, 1993; Shields, 2003) or to protect the bank from further erosion (Abbe et al., 1997; Drury et al., 1999; Shields et al., 2004).

At least three authors have reviewed LWD-related stream restoration projects (Abbe et al., 2003; Bisson et al., 2003; Reich, 2003), and at least one other team reviewed stream restoration projects in the Midwest that reported on the use of LWD as a restoration method (Alexander and Allen, 2006). The aforementioned studies universally recognized that very limited data exist to quantify the success and failure rates of stream restoration projects and of LWD applications in particular. They also agreed that there is an extreme lack of post-restoration monitoring to support such findings. Additionally, like LWD research, the limited studies that have reported on restoration successes and failures have been physiographically limited to the Pacific Northwest.

Reich et al. (2003) reviewed 29 stream restoration projects that used LWD as a key component of restoration and took place between 1976 and 2000. Of all the projects reviewed, the most common goal was to reestablish complexity in the channel, either for fish habitat (common in North America) or for the reestablishment of natural channel form (common in Germany). Similarly, Alexander and Allan (2006) reviewed 1,345 stream restoration projects that took place in the Upper Midwest of the United States between 1970 and 2004 and found that the two most common project goals were habitat improvement and bank stabilization. Although Alexander and Allan reviewed all restoration projects, not just those that used LWD, they found that addition of LWD was the third most common restoration practice, out of 20, behind the application of sand traps, and addition of riprap (Figure 1.1).

Common among each of the studies that reviewed the use of LWD as a restoration tool and others (e.g., Gregory, 2003; Montgomery et al., 2003) is a debate related to the physical placement of LWD. Should LWD structures be anchored, or allowed to move freely? While anchoring trees and rootwads into banks for bank protection purposes has been a common practice (D'Aoust and Miller, 2000; Bisson et al., 2003; Reich et al., 2003; Shields, 2003; Shields et al., 2004; Karle et al., 2005), so-called "soft engineering" methods are becoming increasingly popular (Bisson et al., 2003). Methods considered soft engineering include giving more attention to utilizing LWD of the appropriate size for the site as well as selecting sites where wood accumulation would likely occur under more natural conditions. The shift toward soft engineering techniques reflects the current trend of using “natural” materials to help mimic “natural” processes in an attempt to restore heavily disturbed systems. However, Abbe et al. (2003) explicitly stated that the successful use of LWD in this manner requires an understanding of the watershed and reach-scale context of a project, the hydraulic and geomorphic effects of wood placements, and the possible changes in wood structures over time.

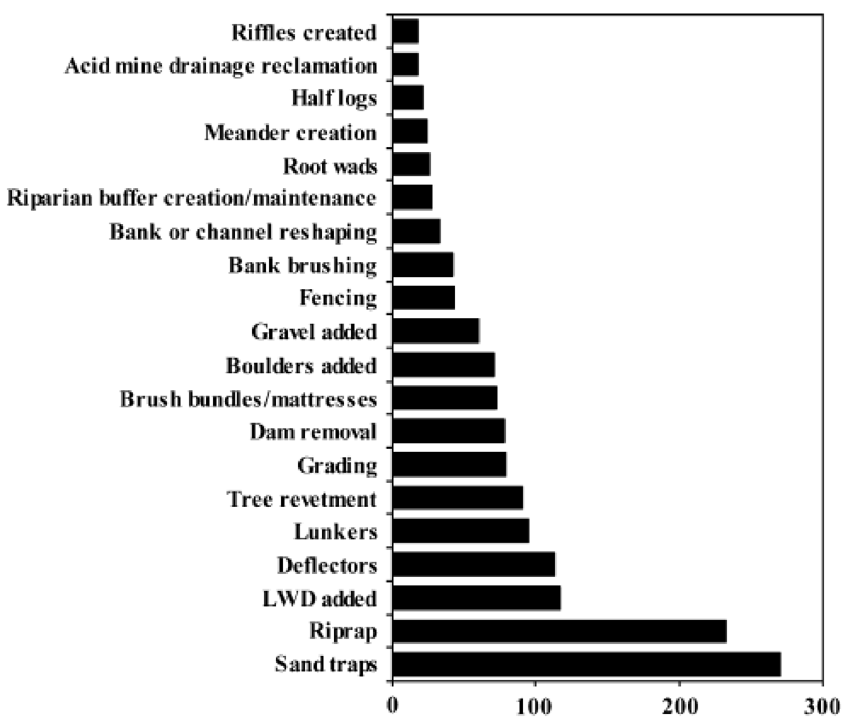

Figure 1.1. Figure from Alexander and Allen (2006) displaying the 20 most implemented stream restoration techniques in stream restoration projects of the Upper Midwest.

1.6. Fluvial Wood and Spatial Scale

Studies of LWD increasingly occur at finer spatial scales (Swanson, 2003). However, multiple spatial scales of analysis are ultimately needed to gain a good understanding of the complex dynamics of LWD in river systems. The trend of finer-scale studies is likely a result of the popularity of LWD as a management tool and the resulting need to understand how a particular piece of wood will affect very local hydrology/geomorphology of the reach being restored. Also, identifying the location and/or characteristics of LWD at very broad spatial scales along medium- to large-sized rivers is often logistically infeasible, which is why the few segment- to watershed-scale studies that have been conducted have been augmented by remote sensing (Abbe and Montgomery, 2003). Multi-scale studies of river systems have the potential to provide a more holistic understanding of those particular systems.

Scale is likely to play a role in our understanding of the link between LWD and fluvial processes. It is known that ecological and fluvial processes occur across multiple scales (Schumm, 1977) and can present substantial challenges for analysis. Traditionally, geomorphologists have taken a top-down approach to investigate trans-scale processes, whereby processes operating at broad spatial scales control morphologic structure at finer spatial scales. However, recent trends in fluvial research have shifted to a more bottom-up approach in which fine-scale structure affects processes at a broader scale (Poole, 2002). This trend has emphasized the need to understand trans-scale processes from both of these perspectives and the need to apply conceptual frameworks that link physical structure and process across spatial scales (Poole, 2002).

The hierarchical patch dynamics (HPD) framework described by Wu and Loucks (1995) provides a key reference for investigating trans-scale linkages between channel form and process within a river (dis)continuum. The HPD perspective views river systems as nested, discontinuous hierarchies of patch mosaics (Poole, 2002). In the case of fluvial geomorphology, the patch mosaics represent the organizational scales of stream ecosystems (Frissell et al., 1986) (Figure 1.2). Within the nested structure in Figure 1.2, the reach is a component of the segment and the habitat unit is a component of the reach. Given this framework, the physical structure of the reach is influenced by both the structural context of the segment and the metastructure of the habitat units. While scale is not a primary focus of this research, this theoretical perspective will help provide a framework for interpreting interactions between LWD and the fluvial system at different scales.

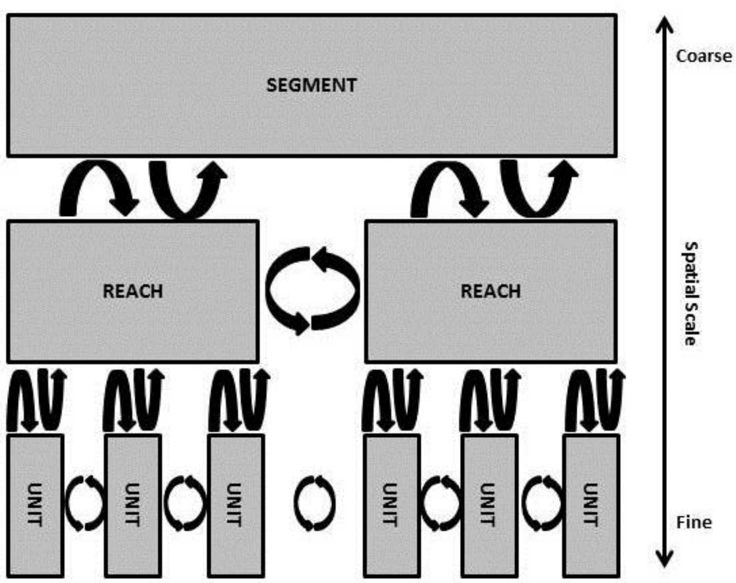

Figure 1.2. Nested-scale framework used in the study design to investigate LWD (modified from Poole, 2002).

1.7. Motivation for Research

The impetus for the research presented here stems from two primary observations of the LWD literature. First, a majority of LWD research has taken place in the Pacific Northwest, or similar physiographic regions around the world; therefore, conclusions should not be taken to be generalizable enough to accommodate river systems outside of these regions. Second, the spatial scales at which most studies have been undertaken tend toward the micro-scale, with a discernible lack of segment- to watershed-scale analyses.

1.8. Objectives

Understanding the geomorphic influences of LWD and the large-scale characteristics of LWD distribution is necessary for the successful implementation of the wood-related management strategies that are now popular and for the successful management of forested riparian ecosystems. The primary objectives of this dissertation research are to:

1) Identify longitudinal patterns of LWD arrangement in the Big River (Chap. 2).
2) Investigate the occurrence of multi-scale LWD arrangement patterns (Chap. 2).
3) Identify geomorphic and riparian control mechanisms of LWD density patterns in the Big River (Chap. 3).
4) Characterize the contemporary, reach-scale wood loads of the Big River (Chap. 4).
5) Investigate the effect of LWD on reach-scale sediment storage in the Big River (Chap. 4).

1.9. Organization of Dissertation

This dissertation consists of five chapters. Chapters 2 through 4 are included as stand-alone manuscripts that will be submitted for publication to ISI peer-reviewed journals. In Chapter 2, I use a suite of spatial statistical techniques to identify large-scale longitudinal arrangement patterns of large woody debris in the Big River of East Missouri. This research identified LWD arrangement patterns that will serve as the basis for understanding the physical and riparian controls of LWD arrangement in the Big River. Additionally, this research has presented spatial statistical techniques as a valuable tool for identify longitudinal patterns in river system components.

In Chapter 3, I investigate potential physical and riparian controlling factors of LWD density along the Big River by performing a series of statistical tests of association between LWD density and a suite of physical and riparian river system variables. Management practices that involve LWD placement, particularly in semi-confined, lower gradient river systems, could have better success rates if they can be based on understanding what controls LWD arrangement.

In Chapter 4, I determine the reach-scale characteristics of LWD and investigate the influence of those characteristics on sediment storage in the Big River. This research was intended to help establish important baseline LWD characteristics for rivers of this type and provide a better understanding of the role that LWD plays in sediment storage, in a river system with a substantial amount of lead-contaminated sediment.

In Chapter 5, I conclude with a summary of the findings of Chapters 2 through 4 and provide a direction for future LWD research. Additionally, I briefly discuss the potential implications of this research as it relates to management applications using LWD. The appendices contain the computer syntax used for the higher level statistical computations, as well as tables containing the raw field data collected for reach-scale analysis and the field data sheet used for the reach-scale LWD inventory.

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Chapter 2: A Geospatial Approach to Identifying Longitudinal Patterns of Fluvial Wood Density in a Midwestern River System

A version of this chapter will be submitted to River Research and Applications for publication by Derek J. Martin and Carol P. Harden.

2.1. Abstract

Large woody debris (LWD) is universally recognized as a key component of the geomorphological and ecological function of fluvial systems and has been increasingly incorporated into stream restoration and watershed management projects. However, “natural” processes of recruitment and the subsequent arrangement of LWD within the river network are poorly understood and thus, rarely a management consideration. In many locations, the lack of understanding has led to the failure of restoration/rehabilitation projects that involved the use of LWD. Managers would greatly benefit from the ability to accurately model LWD distribution. This research used a suite of spatial statistics to investigate longitudinal arrangement patterns of LWD in a low-gradient, Midwestern river. First, a large-scale GPS inventory of LWD, performed on the Big River in the eastern Missouri Ozarks, resulted in over 4,000 logged positions of LWD along seven river segments that covered nearly 100 km of the 237 km river system. A global Moran’s I analysis indicates that LWD density is spatially autocorrelated and displays a clustering tendency within all seven river segments (P-value range = 0.000 to 0.054). A local Moran’s I analysis identified specific locations along the segments where clustering occurs and revealed that, on average, clusters of LWD density (high or low) spanned 400 m. Spectral analysis revealed that, in some segments, LWD density is spatially periodic. Two segments displayed strong periodicity, while the remaining segments displayed varying degrees of noisiness. A wavelet analysis was then performed to identify investigate periodicity relative to location along the segment. The wavelet analysis identified significant ($\alpha = 0.05$) periodicity at discrete locations along each of the segments. The wavelet analysis also identified the existence

of multi-scale periodic patterns. The results of these analyses contribute a new perspective on the longitudinal distribution of LWD in a river system, which should help identify physical and/or riparian control mechanisms of LWD arrangement and support the development of models of LWD arrangement. Additionally, the spatial statistical tools presented here have shown to be valuable for identifying longitudinal patterns in river system components.

2.2. Introduction

Large woody debris (LWD) has become universally recognized as a key component of the ecological and geomorphic functionality of river systems in physiographic regions that support wooded riparian corridors (Gregory et al., 2003a). As a result of this recognition, LWD has increasingly become an important component of stream rehabilitation and management projects in these regions (Reich et al., 2003). In particular, LWD has been widely used to enhance habitat for anadromous fish in rivers of the Pacific Northwest (Bisson et al., 2003) and to serve as a "natural" means of enhancing bank stabilization and geomorphic complexity for stream rehabilitation projects throughout the United States and the world (Abbe et al., 2003; Reich et al., 2003). Additionally, LWD has been investigated for its role in biogeochemical cycling (Bilby, 2003; Seo et al., 2008) and its role in the terrestrial-aquatic carbon interface (West et al., 2011; Wohl and Ogden, 2013). However, the success rate of wood-related rehabilitation efforts has been highly variable, with failures often attributed to a lack of understanding of watershed-scale processes (Frissell and Nawa, 1992; Bisson et al., 2003; Roni et al., 2008). Although an extensive LWD literature exists, understanding of the large-scale processes of LWD recruitment, transport, and arrangement is still in its infancy, particularly when it comes to lower gradient, alluvial river systems, and is likely a cause of management application failures. Our ability to effectively use LWD as a management tool is dependent on our ability to understand how LWD is "naturally" transported and arranged within a river system.

Current theoretical models suggest that the arrangement of LWD along a river network depends on the relationships among source area locations, transport capacity, wood trapping sites, and wood size characteristics (Swanson, 2003). Studies used to exemplify the varying wood dynamics within these models have been done on rivers representing system extremes, using first-order mountain streams (Snyder, 2000) or fifth-order Coastal Plain rivers (Palik et al., 1998). Thus, a wide range of system variability is not accounted for by these models, although a continuum of variability is likely to exist as processes change from headwaters to large-order streams. Additionally, most studies of LWD arrangement patterns have extrapolated theoretical models from small-scale field studies, and few actually have field data to support the identification of LWD arrangement patterns at scales coarser than the reach scale (Gregory et al., 2003b; Swanson, 2003). This is likely a result of the logistical difficulties associated with collecting LWD inventory data at a fine scale over large areas. However, fine-scale inventory data collected over large areas would not only contribute to our understanding of large-scale LWD arrangement patterns, but could also be used to investigate the multi-scale processes that control LWD arrangement. Ecologists have implemented multi-scale pattern identification methods to fish abundance studies along stream networks (Torgerson et al., 2004), but similar methods have rarely been applied to other river system components. Full reach- and basin-scale analyses of LWD represent a critical knowledge gap and are needed to more accurately represent spatial patterns of LWD arrangement, especially as management frameworks increasingly focus on the watershed or drainage basin as a management unit (Swanson 2003).

In this research, we employ a set of spatial statistical methods for identifying LWD arrangement patterns along a low-gradient, alluvial, Midwestern river system. Our objective was to identify LWD arrangement patterns by performing a field-based LWD inventory over a large percentage of the river's main stem, thus having the ability to identify patterns at previously eluded scales. A secondary objective was to investigate any multi-scale LWD arrangement patterns and to investigate those patterns within the context of multi-scale fluvial processes that may control LWD arrangement.

2.3. Study Area

This research was conducted on the Big River, in Eastern Missouri, U.S.A. The Big River flows approximately 220 km northward from its source in the St. Francois Mountains to its confluence with the Meramec River, about 15 km southwest of St. Louis, Missouri (Figure 2.1). Elevations in the watershed range from 200 m to 300 m above mean sea level. The Big River drains approximately 2500 km^2 of primarily rural, agricultural, and forested land. It maintains a relatively constant riparian corridor, although narrow in places, of mostly eastern hardwood and pine tree species, providing a good source of large woody material, and it maintains a relatively well developed floodplain for most of its length. Historical landuse in the watershed follows the patterns prevalent in much of the rest of the Ozark region, whereby clear-cut logging was the dominant landuse practice from the mid-1800s to the early 1900s, followed by more riparian land clearing for agriculture in the early 1900s (Jacobson and Primm, 1994). Therefore, riparian forests along the Big River are relatively young in age.

The Big River watershed has a varied geology. The St. Francois Mountains, the river's source region, are of igneous origin; however, the remainder of the watershed is primarily underlain by dolomite, with some limestone and shale units. The dominance of carbonate rock in this region has resulted in extensive karst development (Rafferty, 1980). The chert content of limestone and dolomite is quite high in the Ozarks. Therefore, accumulations of weathered bedrock often contain large amounts of chert gravel, which is the dominant bedload of streams in the Ozarks, including the Big River. Although the dominance of gravel in Ozark streams is a natural phenomenon, many Ozark streams are experiencing excessive gravel loads that may be associated with historic landuse activities (Saucier, 1983; Jacobson and Prim, 1994; Jacobson and Gran, 1999; Panfil and Jacobson, 2001; Jacobson, 2004).

The Big River drains what is known as "the Old Lead Belt." The Old Lead Belt is a sub-district of the larger Southeast Missouri Lead Mining District, a national leader in the production of lead and zinc ore between 1869 and 1972 (Pavlowsky, 2010). Much of the mine waste material, or chat, still remains in the form of large chat piles. The highly contaminated chat now makes up a relatively substantial portion of the Big River's bedload. In 1992, portions of the Big River watershed were listed on EPA's Superfund National Priorities List for lead contamination after studies revealed numerous adverse human health impacts (Asberry, 1997; Gunter, 2011). Additionally, impacts to wildlife range from reduced abundance, diversity, and density of freshwater mussels (Buchanon, 1979; Schmitt et al., 1987; Roberts and Bruenderman, 2000;

Roberts et al., 2009) to elevated levels of lead in crayfish (Allert et al., 2010) and other fish, resulting in fish consumption advisories along the Big River (MDHSS, 2011). The LWD study presented here is part of a larger effort to understand the dynamics of contaminated sediment in the Big River by investigating the extent to which LWD stores fluvial sediments.

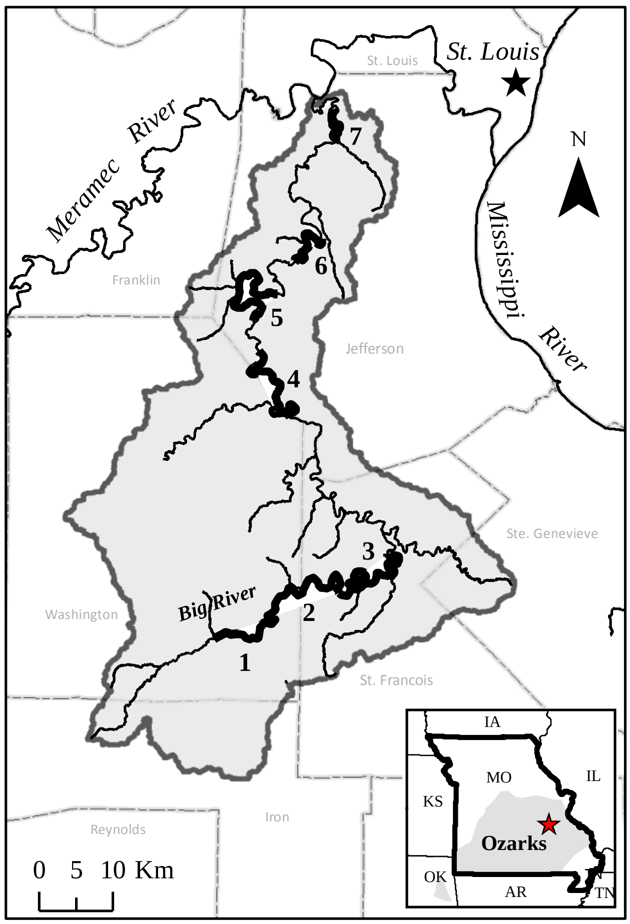

Figure 2.1. The location of the Big River, Big River watershed and major tributaries of the Big River in the Midwestern United States. Bold lines represent segments where LWD inventories were done.

2.4. Methods

2.4.1 *Field Data Collection*

For this study, we conducted a broad-scale LWD inventory. LWD was defined as any piece of wood located within the bankfull channel and greater than 1 m in length and 0.10 m in diameter. The river segment (length of river between major tributaries) served as the primary spatial sampling unit. The location of every piece of LWD was recorded with a GPS along seven segments of the Big River. The studied segments were distributed along the mainstem of the river, from the uppermost section of the watershed to the river's confluence, to represent the various geologic, landuse, and slope conditions (Figure 2.1). A canoe was used to access the entire length of each segment; thus, river access and shuttle convenience were additional considerations for segment location. One person operated the canoe while the other used a GPS to record the location of each piece of LWD.

2.4.2 *Spatial Analysis*

Spatial patterns of LWD arrangement were investigated by identifying changes in LWD density over river distance. Each river segment was subdivided into 100-m sections. Within each section, the number of LWD were tallied and attributed to the center point of the respective 100-m section (Figure 2.2). The 100-m interval was chosen because it provided density measurements at a relatively fine resolution, and for the purpose of comparability with other studies.

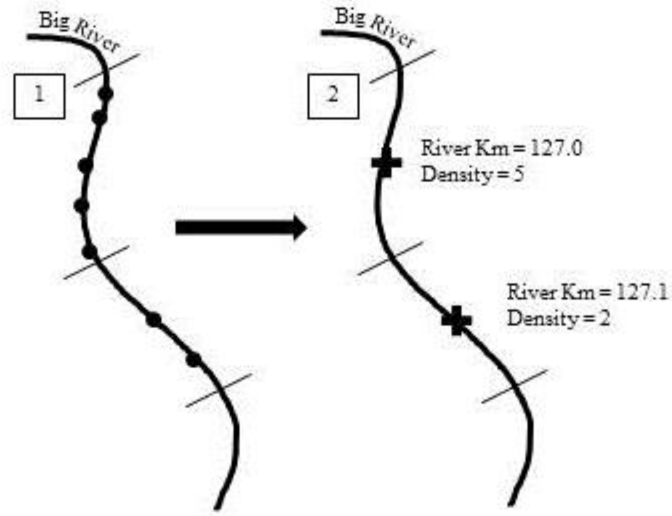

Figure 2.2. Schematic representation of the LWD density dataset used for spatial analysis. Black dots represent LWD and the black crosses represent the center point of the 100-m section.

Theoretical models of LWD arrangement suggest that lower gradient alluvial rivers, such as the Big River, should display random patterns of LWD arrangement (Swanson, 2003). To determine if the data displayed spatial autocorrelation, we performed Moran's I tests for spatial autocorrelation within each of the seven river segments. Moran's I is a popular index of spatial autocorrelation that is most often applied to areal data. In this case, however, the LWD dataset is one-dimensional, consisting of equally spaced (100 m) data points along the center line of the river. Thus, the true x- and y-coordinates of the data points were arbitrarily reassigned, holding the y-coordinate constant, and assigning the x-coordinates as sequential 100-m intervals, maintaining their original order along the river segment.

A combination of global Moran's I (Moran, 1950) and local Moran's I (Anselin, 1995) tests were performed to characterize the nature of autocorrelation within the LWD density dataset, and serve as an exploratory first step in characterizing spatial patterns of LWD arrangement in the Big River. For both the global and local tests, a fixed distance method was used which equally weights all features within the analysis window, as opposed to other methods which place higher weights on points nearest to the target feature and lower weights to those farther away. In this case, a fixed distance of 100 m was used in order to assess autocorrelation at the finest scale of measurement possible. A fixed distance of 100 m ensured that every feature has two neighbors, one upstream and one downstream, with the exception of the end points. The global Moran's I test provides a single index value for the entire segment along with a z-score and p-value, indicating whether the data are significantly autocorrelated and whether the data, as a whole, are clustered, dispersed, or random. The Local Moran's I test provides an index value, z-score, and p-value for each individual feature within the dataset, and indicates outliers and the nature of the autocorrelation of that feature: high values surrounded by high values, low values surround by low values, high values surrounded by low values, or low values surround by high values. All Moran's I tests are interpreted within the context of the null hypothesis of complete spatial randomness and were performed using ArcGIS Spatial Statistics Tools

Longitudinal patterns of LWD density were then investigated by performing a spectral analysis of the spatial data series. Spectral analysis is a popular method for identifying cyclical, or periodic components of one-dimensional datasets, particularly in the fields of economics (Hamilton, 1994), and climatology (Ghil et al., 2002). Spectral analysis is presented here as an equally valuable tool for identifying periodic behavior of data along a river channel. First, 100-m LWD density was plotted over distance for each of the seven river segments. Then, periodograms were calculated for each of the seven river segments. Periodograms display the dominant frequencies, or periods, detected in a dataset by comparing fluctuations in the dataset to sinusoidal waves of known frequencies. The periodogram shows, essentially, the sum of the sinusoidal waves that best fit the data series and displays that as a power spectrum. Spikes on the periodogram represent the dominant frequencies, or periods, within the dataset. Periodograms that display multiple significant spikes indicate component, or harmonic, frequencies which, in the context of the LWD density dataset, would indicate dominant frequencies at different spatial scales. For a more in-depth explanation of the mathematical derivation of periodograms, see Woodward et al. (2011).

The spectral analysis provides an overview of the dominant frequency, or frequencies, of the data series; however, in the case of many data series, frequencies are likely to vary over time or space. Wavelet analysis is a popular method for measuring localized variations in frequency over time (Torrence and Compo, 1998; Percival and Walden, 2000), and as such, is applied here to measure localized variations over space. Rather than attempting to fit a sinusoid of a single frequency to the entire data series, as the spectral analysis does, a wavelet analysis moves a smaller window of a sinusoid (the wavelet) along the data series. Changes in frequency over space can then be identified by continuously changing the size and frequency of the wavelet. The wavelet analysis provides a two-dimensional, continuous graphical output of frequency, or period, over distance with statistically significant ($\alpha = 0.05$) frequencies flagged, and a cone of influence indicating results affected by edge effects. For a more in-depth explanation of wavelet analysis, refer to Torrence and Compo (1998). Spectral analysis and wavelet analysis were performed in RStudio version 0.98.501.

2.5. Results and Discussion

The LWD inventory of all seven river segments resulted in a tally of 4,010 total pieces of LWD. Table 2.1 shows the descriptive geomorphic characteristics of each of the seven segments to display the changing physical characteristics of the segments from segment One (upstream) to segment Seven (downstream). Table 2.1 also displays the LWD tally and length-averaged LWD density for each segment. Segment Seven contained the highest average LWD density, of 64 LWD/km, and segment Two contained the lowest average density, of 33 LWD/km. No downstream trend is identifiable in length-averaged density from one segment to the next.

Table 2.1. Descriptive characteristics of each river segment.

Segment	Length (km)	N (100m intervals)	Slope	Sinuosity	Avg. Width (m)	# of LWD	LWD/km
1	10.7	107	0.00165	1.37	21	630	59
2	21.7	217	0.00074	2.11	24	718	33
3	21.7	217	0.00074	2.58	20	953	44
4	12.9	129	0.00047	1.90	31	726	56
5	7.4	74	0.00053	1.19	35	104	55
6	12.9	129	0.00023	2.69	37	487	38
7	6.1	61	0.00049	1.42	35	392	64

2.5.1 *Spatial Autocorrelation*

Large woody debris density was spatially autocorrelated within each of the seven river segments. The global Moran's I test for spatial autocorrelation resulted in rejection of the null hypothesis that LWD density is randomly distributed (Table 2.2). Autocorrelation was significant at a 95% confidence level within each of the river segments, with the exception of segment Seven, in which it was significant at the 90% confidence level. Additionally, positive z-scores for all river segments indicate that LWD density is more spatially clustered, as opposed to dispersed, than would be expected if LWD density were random. This likely indicates that 100-m sections with high LWD density are located near other 100-m sections with high density, and 100-m sections with low density are located next to other 100-m sections with low density. However, the local Moran's I analysis will determine the specific nature of the clustering patterns. Segment Seven produced the lowest z-score. Although still significant at the 90% confidence level, this suggests that patterns of LWD density are nearer a random distribution than the other segments, potentially indicating a weakening of the underlying spatial process controlling LWD density in segment Seven. Alternatively, segment One produced the highest z-score and thus displays a level of clustering that is farthest from random among the seven segments.

Table 2.2. Global Moran's I results for each river segment using LWD density as the autocorrelation variable.

Segment	Moran's I	Z-Score	P-Value
1	0.433	4.752	0.000
2	0.176	2.688	0.007
3	0.223	3.403	0.001
4	0.189	2.787	0.005
5	0.341	3.092	0.002
6	0.318	3.215	0.001
7	0.219	1.923	0.054

The local Moran's I test revealed the locations along each segment where clustering and outliers occur (Figure 2.3). Each segment contained at least two locations where statistically significant (0.05) clustering occurred. High-density clusters accounted for 2.3% of the total length of river inventoried, followed by low-density clusters (1.6%), low-density outliers (0.4%), and high-density outliers (0.3%). On average, the number of consecutive autocorrelated features was two, indicating that, on average, clustering of the 100-m density points occurs over a distance of 200 m (Figure 2.4).

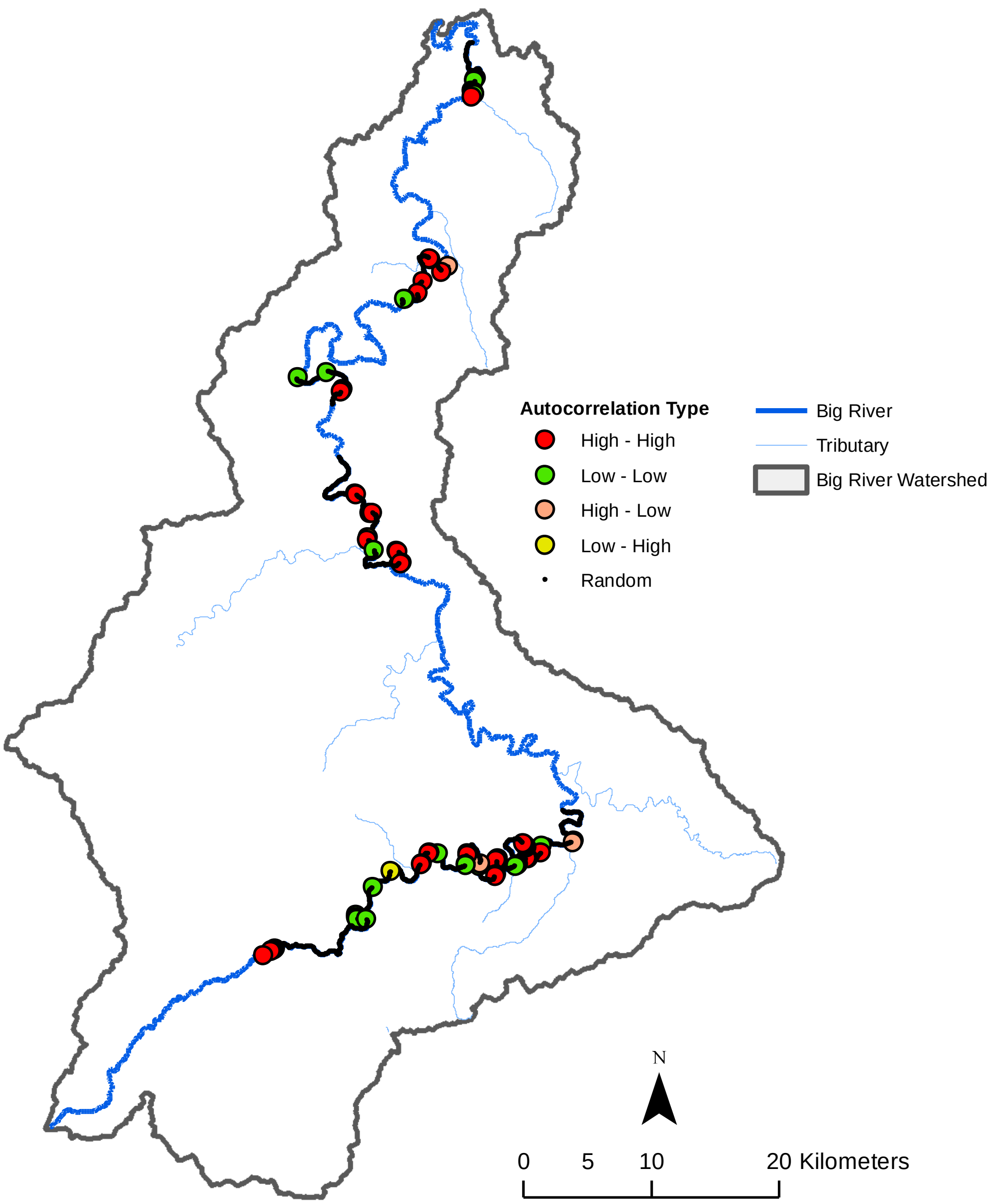

Figure 2.3. The local Moran's I analysis shows the locations of high density clusters (HH), low density clusters (LL), high density surrounded by low density outliers (HL), and low density surrounded by high density outliers (LH).

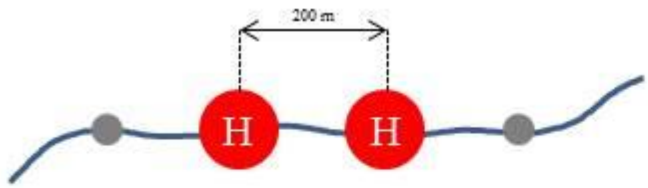

Figure 2.4. The average number of consecutive autocorrelated features was two, indicating that on average, clustering of LWD occurs over a distance of 200 m.

2.5.2 *Density Plots*

Downstream variation in LWD density was initially investigated by analyzing plots of LWD density over distance (Figure 2.5). A five-point moving average was applied to each of the plots to reduce data noise and aid the initial visual interpretation of the density plots and to identify any data trends. No obvious longitudinal trend was identified in any of the segments. Visual interpretation of the moving average did, however, reveal a potential periodicity within many of the segments, particularly Segment Six (Figure 2.5). The regularity of the periodic signal appears to become stronger in the downstream direction, from segment Two to segment Six, and is most obvious in segment Six.

2.5.3 *Periodicity of Wood Deposition*

Spectral analysis revealed the periodic nature of LWD density within each of the river segments. The dominant periodic signals are expressed as spikes within the periodograms of each of the seven segments (Figure 2.6). The x-axis distances (m) of the periodograms in Figure 2.6 are plotted over a log scale to more easily differentiate and emphasize the spikes that indicate

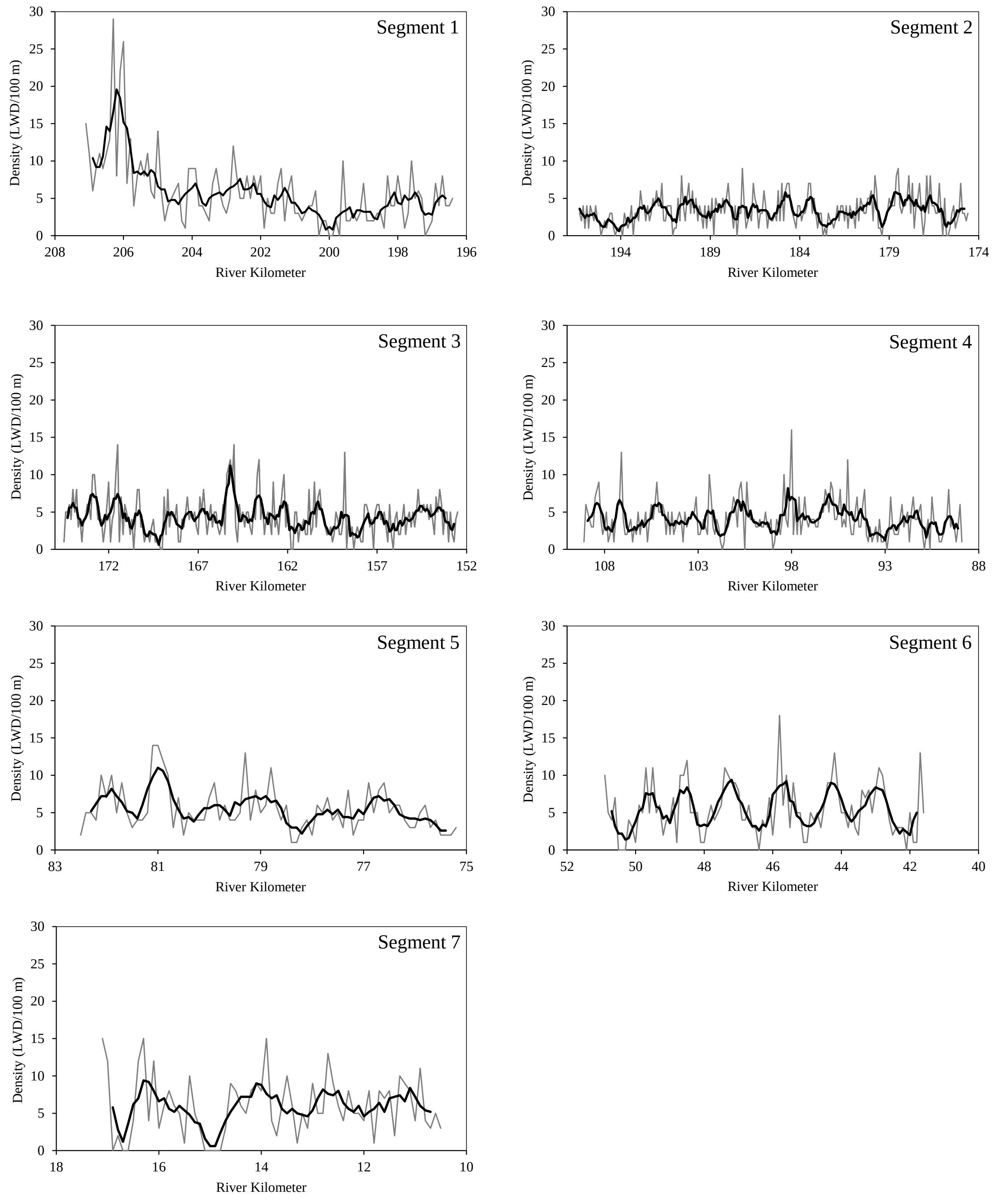

Figure 2.5. LWD density plotted over distance for each 100-m river segment. The bold line represents a five-point moving average for aided visual interpretation.

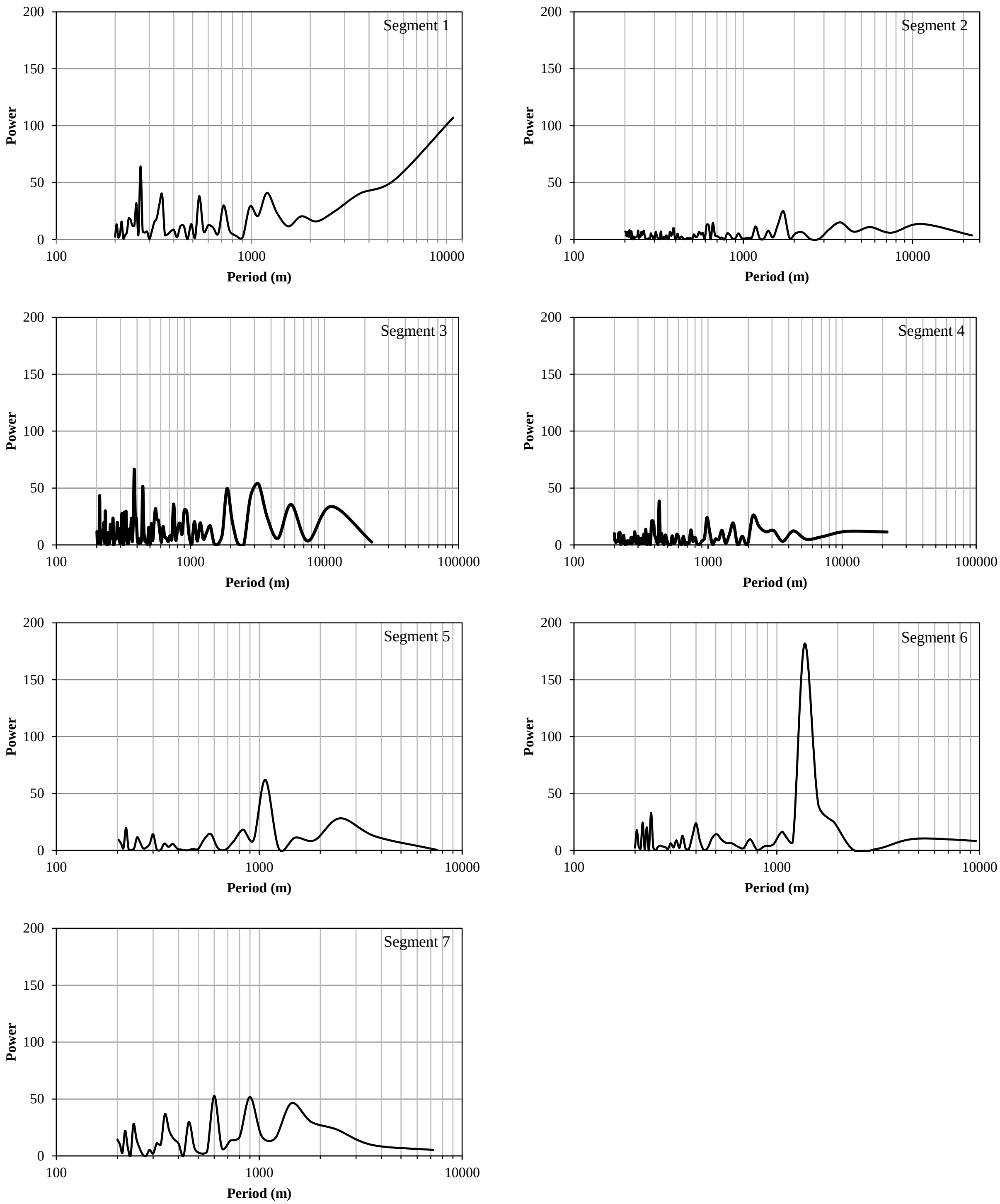

Figure 2.6. Periodograms for each river segment. Peaks represent strength of periodic signal detected. Because space was substituted for time, the “period” is a distance along the river.

a dominant periodic signal. However, the log scale also produces a false spike on the right side (longer distances) of most of the periodograms due to compression of the data at longer distances. Interpretation of the periodograms was approached cautiously because, due to their relatively short length, the data series are highly sensitive to edge effects and, thus, the validity of the periodic signal is substantially reduced at distances approaching the entire segment length. The periods represented by the dominant spikes range from 270 m to 1,371 m (Table 2.3).

Table 2.3. Dominant periods were found in segments 1, 5, and 6.

Segment	Primary Peak (m)	Secondary Peak (m)	Tertiary Peak (m)
1	270	348	1,200
5	1,071	NA	NA
6	1,371	NA	NA

The spectral analysis found dominant periods ranging from 270 m to 1,371 m among the segments. Based on the strength of the dominant periodic signature, relative to noise, within each periodogram, LWD density was most periodic in segments One, Five, and Six, with dominant periods of 270 m, 1,071 m, and 1,371 m, respectively. The strongest periodic signature occurred in segment Six, followed by segment Five, and then segment One. Periodograms for segments Two, Three, Four, and Seven lack a dominant spike and thus indicate that LWD density is likely not periodic in these segments. Although the spectral analysis did not identify a dominant periodic signal for segments Two, Three, Four, and Seven the wavelet analysis identified significant periodic signals at discrete locations within all of the segments.

2.5.4 *Wavelet Analysis*

The wavelet analysis identified the strength of the dominant periodic signals at specific locations within each of the river segments. Figure 2.7 displays the output spectrograms from the wavelet analysis of each segment. The region of the spectrograms overlapped by diagonal lines represents the cone of influence, or the region impacted by edge effect, and is thus not considered during plot interpretation. Additionally, the bold black contour lines on the spectrograms represent the 95% confidence level: the regions within the bold contours are considered significant.

The longitudinal consistency of periodic LWD density varies among the segments (Figure 2.7). Segment Six displays the highest level of periodic consistency. A significant periodicity of 1000 to 2000 meters, consistent with the spectral analysis, persists for the entire length of the segment outside of the cone of influence. The remaining segments display varying degrees of periodic consistency, with segments One and Seven displaying the least amounts of periodicity and consistency. Segments Two, Three, Four, and Five display significant periodicities at multiple spatial scales. Segment Four, in particular, displays a consistent periodicity between 1800 and 3200 meters between river kilometer 96 and 104, as well as a periodicity between 300 and 500 meters at what appear to be hierarchically nested locations within the same segment. Segments Two and Three also display significant periodicities at multiple scales, although not hierarchically nested as in segment Four. Finally, segment

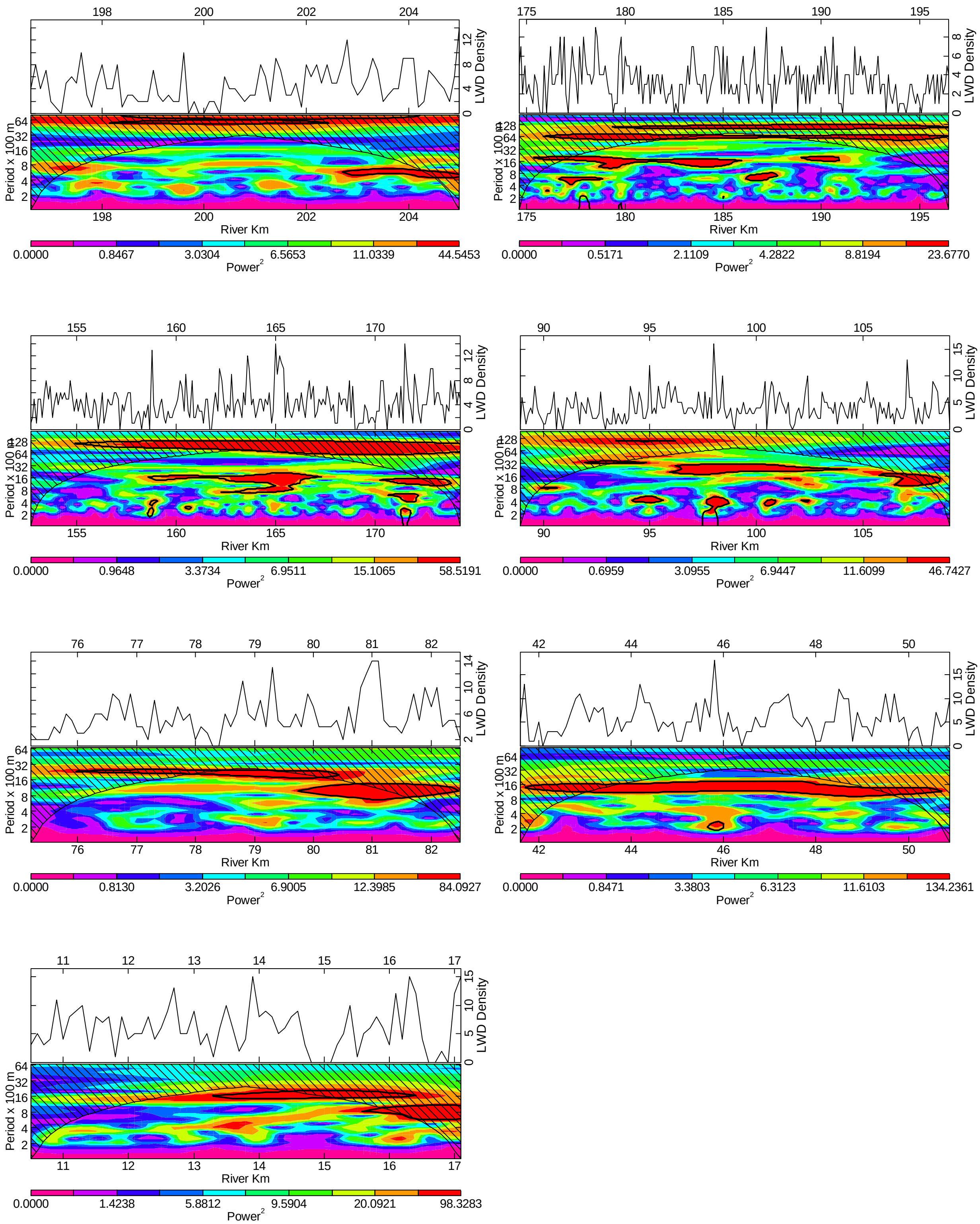

Figure 2.7. Wavelet analysis of LWD density in each river segment. The regions enclosed within the bold, black contour lines represent statistically significant periodicities.

Seven only displays a short length of significant periodicity, between 1,400 and 2,000 meters.

The wavelet analysis revealed that the periodic signals identified through spectral analysis are not consistent along the entire length of the segments, with the exception of segment Six, and thus have important implications for modeling wood distribution dynamics. The periodic arrangement of LWD occurs in discrete, intermittent locations and often displays multiple scales of periodicity. Identification of this multi-scale, intermittent periodicity suggests that large-scale models of wood dynamics, such as those described in Gregory et al. (2003) that focus on linear processes of recruitment and decomposition, likely lack the ability to account for these periodic patterns over large spatial scales. Moreover, the primarily deterministic models of wood dynamics that currently exist have been developed from field data collected in streams of the Pacific Northwest, where recruitment processes and deposition site controls are well known and are likely to differ greatly from those of Midwestern rivers, such as the Big River. Given the variability of periodic patterns identified along the segments of the Big River through spectral and wavelet analysis, the previously developed deterministic models will likely be ineffective for modeling/predicting wood arrangement, particularly in rivers like the Big River.

2.6. Conclusions

The spatial analyses conducted here can provide location-specific guidance for those trying to understand physical controls on LWD arrangement in the Big River. The local Moran's I analysis was able to identify specific locations where LWD densities are significantly high or low, and where important LWD density outliers are located. The spectral analysis identified periodic patterns of LWD arrangement in three of the seven segments. The dominant periods identified in those segments can now be investigated within the context of the morphological and riparian characteristics of those segments to help identify potential controls on LWD arrangement. The wavelet analysis will serve to guide that effort by providing specific information on exactly where within the segments significant periodicities occur. Numerous physical parameters can be measured at those locations and, ultimately, associated with the periodic signal. If significant relationships are found, we can then proceed to model wood distribution based on a known physical parameter.

Stream restoration and management projects would greatly benefit from having the ability to accurately model wood distribution and understand the "natural" LWD arrangement patterns that occur in Midwestern rivers. Additionally, the spatial analysis techniques used here have shown to be effective tools for identifying longitudinal patterns of LWD and could easily be applied to other river system components. For example, Chin (2002) successfully applied spectral analysis to evaluate the periodic nature of step-pool sequences in mountain streams. These tools can also help us understand the trans-scale form and associated function of longitudinal river system components.

2.7. Acknowledgements

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Chapter 3: Identifying Control Mechanisms of Fluvial Wood Distribution Patterns in Missouri's Big River

A version of this chapter will be submitted to The Journal of Environmental Management for publication by Derek J. Martin, Carol P. Harden, and Robert T. Pavlowsky.

3.1. Introduction

Large woody debris (LWD), or fluvial wood, contributes significantly to the ecological and physical functionality of river systems (Gregory et al., 2003a). Growing understanding of the importance of these contributions has been exemplified by the vast accumulation of literature on the subject and by the increasing frequency with which LWD is being utilized in stream rehabilitation (Reich et al., 2003). However, success rates of management applications using fluvial wood are highly variable. Failures of these management applications have been linked to a lack of understanding of watershed-scale morphodynamics and fluvial wood dynamics (Bisson et al., 2003; Roni et al., 2008). Research addressing these topics rarely occurs at scales broader than the reach scale and also tends to be biased toward higher gradient, montane fluvial systems. Consequently, we are uncertain of the ability of theoretical and numerical models of fluvial wood deposition to account for the wide range of variability encountered in fluvial systems.

3.1.1 *Large Woody Debris Dynamics*

The relationships between LWD and the physical and riparian characteristics of river systems vary substantially with changes in land use and riparian tree species, the climatic and hydrological regime, the geomorphological settings, and the watershed management context (Gurnell et al., 2002). These relationships ultimately control the recruitment, transport, and deposition of LWD along and within a river system.

LWD is recruited to the stream channel through a variety of different mechanisms. A majority of studies conducted on LWD recruitment identify mortality of riparian trees as the primary source of LWD recruitment, in addition to bank erosion, fire, mass wasting events, and other mechanisms (Benda et al., 2003). Processes of recruitment vary substantially by region in relation to dominant weather patterns, topography, and the age of the riparian forest. For example, most LWD research has been conducted in the Pacific Northwest region of North America, where many old-growth forests still exist and thus have a higher probability of tree mortality, and where steeper slopes, combined with high levels of precipitation, induce frequent mass wasting events. Benda et al. (2003) recognized the importance of identifying regional differences in wood recruitment processes, especially for the purpose of riparian management. Wood recruitment processes ultimately affect the amount of LWD in the channel and, subsequently, the longitudinal arrangement of LWD along the channel.

In general, field research has shown that the amount of LWD in studied fluvial systems decreases in the downstream direction, as high input rates, combined with low transport capacity in low-order reaches, grade to low input rates with high transport capacity in high-order reaches (Swanson, 2003). However, the characteristics of transport and the subsequent deposition of LWD along the river network vary substantially as a result of variations in wood size, wood availability, and the transport ability of the stream (Swanson, 2003).

In general, LWD already in the channel is prone to accumulate in situations where the wood is more likely to come in contact with the bank or bed (Nakamura and Swanson, 1994). Wide, sinuous reaches, where the channel curvature is likely to force LWD along an outside bend or onto alternate bars, are more prone to LWD accumulation than straight, narrow reaches with high shear stresses and lack of bar development. Some research shows that channel width and sinuosity are the primary factors that control the abundance and distribution of LWD, suggesting that wide channels bordered by floodplains and terraces possess abundant LWD storage sites and that sinuous reaches tend to form secondary channels along valley walls that trap LWD during high flows (Nakamura and Swanson, 1994). Tributary junctions may also be significant LWD storage sites (Nakamura and Swanson, 1994; Swanson and Lienkaemper, 1979). Additionally, Braudrick and Grant (2001) performed a flume study in which they determined that the distance traveled by LWD is significantly related to the ratios of the piece length to average channel width and piece length to maximum radius of curvature of the channel. They also determined that large pieces can move farther than small pieces if the distribution of potential storage sites is infrequent, allowing the built up momentum of a moving piece of LWD to overcome channel roughness elements. The research mentioned above demonstrates the wide range of potential controls on fluvial wood distribution across a wide variety of system types, and thus the inherent complexity in attempting to model such distributions.

3.1.2 *Existing Models of Fluvial Wood Dynamics*

Numerous attempts have been made to model the complex dynamics of LWD, and have been met with varying levels of success (Gregory et al., 2003b). Gregory et al. (2003b) reviewed 14 models of fluvial wood dynamics that had been developed over the previous two decades and found that models of wood dynamics have been primarily used to (1) understand the processes that shape the abundance and distribution of wood at local sites or along river networks and the interactions among those processes, or (2) predict the abundance and distribution of wood that would result from different types of riparian forests as a basis for management decisions. Additionally, they found that 11 of the models reviewed had been developed for the Pacific Northwest, two for the Midwest region, and one for the Rocky Mountain region of North America. All 14 models are mathematical models developed from conceptual descriptions of selected processes of fluvial wood dynamics. They primarily involve delivery of wood from riparian stands.

From their review of existing models of fluvial wood dynamics, Gregory et al. (2003) constructed a conceptual diagram, revealing the existing conceptual understandings of the mechanisms responsible for specific fluvial wood-related processes. The diagram places wood transport (and thus, distribution) at the lowest level of conceptual understanding, calling attention to the need to better understand this particular process.

In the Big River of East Missouri, prior research has indicated that the density of LWD (LWD/100 m) in the channel lacks a significant longitudinal trend, but displays varying degrees of clustering and periodicity and is thus not randomly distributed (Martin and Harden, Chapter 2). The objective of this research is to identify potential control mechanisms of LWD density and of the spatially periodic pattern of LWD density in the Big River. This research provides a perspective from the Midwestern United States on fluvial wood dynamics as well as a broader-scale field perspective on deposition patterns of fluvial wood. Results from this research are intended to serve as a first step toward developing better theoretical models of fluvial wood distribution in lower-gradient, semi-confined, alluvial river systems like the Big River and, ultimately, to help inform decisions related to fluvial wood placement during rehabilitation and management applications.

3.2. Study Area

This research was performed on the Big River, located in the Eastern Missouri Ozarks, USA. The Big River exemplifies a relatively low gradient, semi-confined alluvial river system with some well-developed floodplains and a consistent, wooded, riparian corridor. The Big River flows northward approximately 220 km from its source in the St. Francois Mountains to its confluence with the Meramec River, which eventually drains into the Mississippi River about 20 km south of St. Louis, Missouri (Figure 3.1). Elevations in the watershed range from 414 m at the top of the watershed to 124 m at the river's confluence with the Meramec River. Although the Big River system is primarily alluvial, it exhibits characteristics of a confined meandering system, such as irregular variation of valley widths in the downstream direction. The seven river segments investigated for this study (Figure 3.1) are primarily located in low-gradient sections of the river, with the exception of segment One, which has comparatively high slopes for nearly half of its length. Segment One, with an average slope of 0.002, was investigated for the purpose of contrast and comparison with the other segments, which all have substantially lower slopes, ranging from 0.0007 to 0.0002 (Figure 3.2).

3.3. Methods

A previous study identified a non-random, clustered arrangement of LWD within each of seven segments of the Big River. Numerous reaches within those segments displayed a significant periodic arrangement of LWD (Martin and Harden, Chapter 2). This study uses the same LWD inventory dataset, along with GIS-derived physical and biological river system variables, and a multi-scale experimental design to identify possible control mechanisms of LWD density and periodic arrangement of LWD.

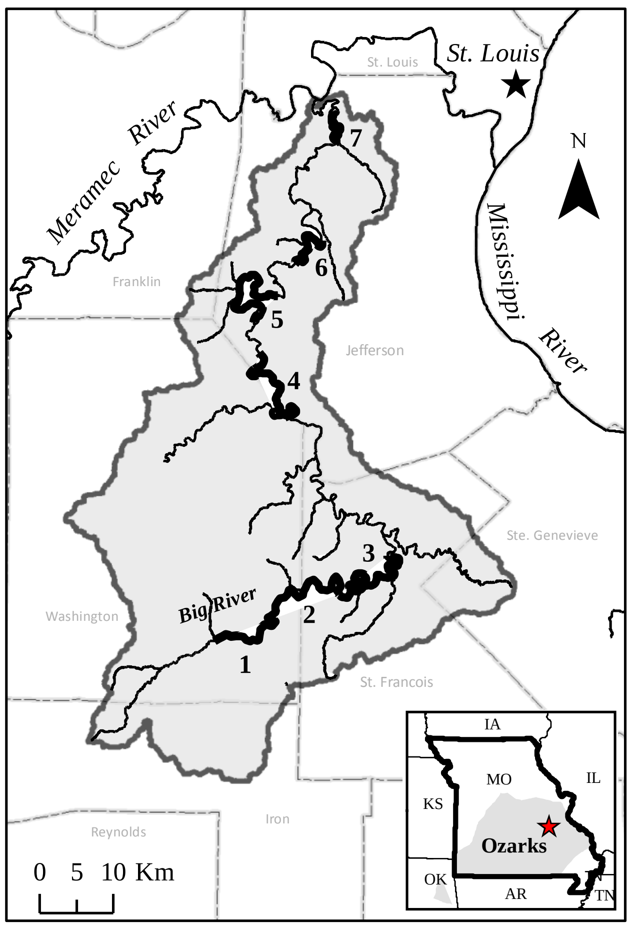

Figure 3.1. The Big River, located in the Midwestern state of Missouri. Bold black lines indicate segments of the river investigated for this study.

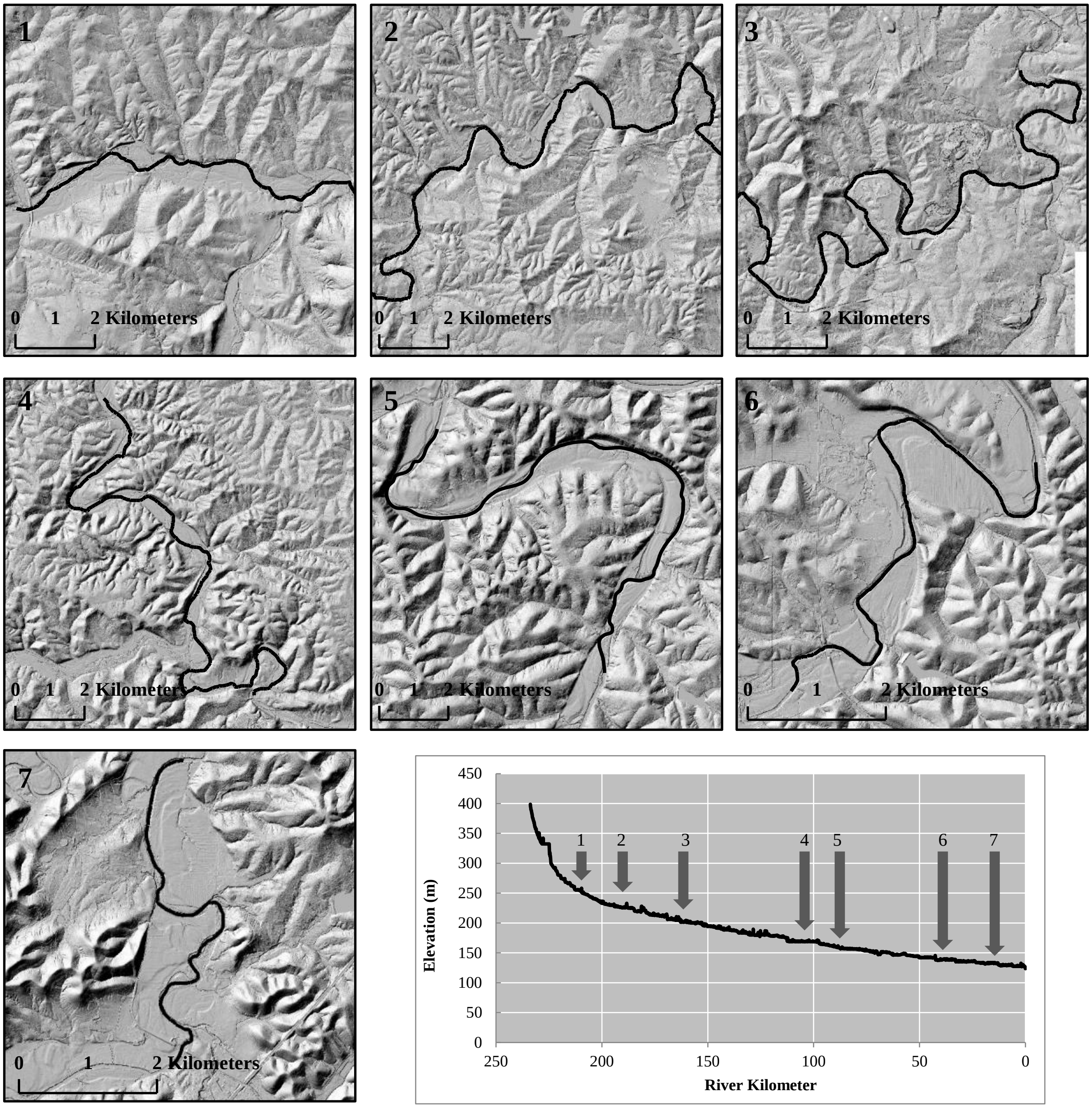

Figure 3.2. Shaded relief maps of each inventoried segment display the extent of floodplain development in each segment and the local topographic context of the segment. All maps are oriented with North at the top of the map. The graph shows location of each segment with respect to the river's longitudinal profile.

The field-based LWD inventory covered seven segments of the Big River, totaling about 100 km, or about 45% of the total length of the river. Segment locations were chosen based on a combination of accessibility, tributary locations (located between at least two third-order or higher tributaries), and location within the river network, in an effort to include segments that exemplify the range of downstream channel morphologies. In each segment, a GPS was used to record the location of all pieces of wood greater than 1 m in length and 10 cm in width, resulting in a point dataset containing over 4,000 LWD piece locations.

LWD density was then calculated in a GIS. Each river segment was subdivided into 100-m sections, and the number of LWD within each 100-m section was counted. The 100-m density was then attributed to the center point of each 100-m section, producing a point dataset of equally spaced LWD density measurements (Martin and Harden, Figure 2.2 , Chapter 2).

3.3.1 *Control Mechanisms of LWD Arrangement*

Studies performed in regions other than the Midwest have identified a variety of potential geomorphic and riparian control mechanisms of fluvial wood distribution (Gregory et al., 2003). For this study, we investigate those, and other possible control mechanisms of fluvial wood arrangement in the Big River. Previously identified controls included in this analysis are channel width, sinuosity, slope, meander wavelength, and gravel bar spacing. Other controls that we investigate are channel condition (disturbed or stable), downstream distance from large tributaries, gravel bar area, and a riparian variable: wooded riparian width. Sinuosity, meander wavelength, and gravel bar spacing are inherently periodic, or rhythmic, in their longitudinal expressions and are thus investigated separately as potential controls on the periodic nature of LWD distribution. Table 3.1 provides a description of each of these variables.

Martin and Harden (Chapter 2) identified the periodic distribution of LWD within the same segments shown in Figure 3.1. They (Chapter 2) used spatial statistical analyses to identify if LWD is in fact arranged periodically, and if so the dominant period (distance between maximum densities) within each segment, and identified specific reaches, within the segments, that displayed statistically significant periodicities. The dominant period within each segment was determined using a spectral analysis, and the reach-scale periodicities were determined using a wavelet analysis. These statistical methods are frequently used to determine periodicity and estimate the strength of a periodic signature of a wave form at multiple scales as it relates to periods of time (Percival and Walden, 2000) or distance (Bradshaw and Spies, 1992; Torrence and Compo, 1998).

Spectral analysis showed that three of the seven segments displayed a dominant periodic signature. The wavelet analysis showed that LWD density was arranged periodically in at least one location along each of the segments. Table 3.2 lists the dominant period within each segment, the reach locations within each of the river segments that displayed significant periodic arrangement of LWD, and the corresponding range of significant periods. The presence of multiple significant periods in some river segments indicates that periodicity was detected at multiple scales within that segment, or that the signal was extremely variable.

Table 3.1. Physical parameters investigated as potential control mechanisms of LWD density in segments of the Big River, Missouri.

Variable	Description
LWD Density	Number of pieces of wood within the 100-m section
Channel Width	Average of five wetted channel width measurements (m) over the 100-m section
Valley Width	Width of valley (m) measured perpendicular to the valley centerline at each datapoint as distance across the 100-year floodplain
Confine. Ratio	Ratio of channel width to valley width
Trib. Distance	Distance downstream from the nearest tributary of 3rd order or higher
100-m Sinuosity	Channel sinuosity measured over each 100-m section
500-m Sinuosity	Channel sinuosity measured over 500 m; 250-m upstream & 250-m downstream of point
1000-m Sinuosity	Channel sinuosity measured over 1000-m; 500-m upstream & 500-m downstream of point
Bar Area	Area of exposed gravel bar (m^3) present in the 100-m section of channel
Drainage Area	Drainage area (km^2) measured from the center point of the 100-m section
RB Wood Width	Percentage of riparian zone covered by woody vegetation, along a 50-m transect running perpendicular to the right bank
LB Wood Width	Percentage of riparian zone covered by woody vegetation, along a 50-m transect running perpendicular to the left bank
Tot. Width	Total percentage of riparian zone covered by woody vegetation on both banks
Elevation	Elevation (m) measured at the center point of the 100-m section
Slope	Slope measured from the upstream end of the 100-m section to the downstream end of the 100-m section
Meander Wavelength	Segment-averaged length (m) of one full meander. Measured from meander apex to meander apex
Gravel Bar Spacing	Segment-averaged distance (m) between gravel bars, or gravel bar complexes (m)
Segment Sinuosity	Sinuosity, as measured from the top of the segment to the bottom of the segment

3.3.2 *Statistical Analysis of Associations*

First, the dominant period identified in segments One, Five, and Six were compared with segment-averaged bar spacing, meander wavelength, and sinuosity. With only three segments yielding a dominant period, statistically valid comparisons cannot be made, however period and the segment averaged variables were still plotted to provide a basis for discussion of the potential relationships.

Table 3.2. Locations of significant periodicity within each of the seven segments of the Big River. Data adapted from Martin (Chapter 2).

Segment*	Dominant Period (m) (From Periodogram)	Period Range (m) (From Wavelet)	Reach Location (River km)
1(a)	270	100-300	203-205
2(a)	NA	900-1800	177-186, 189-191
2(b)		400-700	177-179, 186-188
3(a)	NA	800-2000	158-167, 170-173
3(b)		500-800	171-172
4(a)	NA	1600-3200	96-104
4(b)		900-1600	106-108
4(c)		200-500	94-96, 97-98, 100-101, 102.3-102.5
5(a)	1071	2000-2400	78-80
5(b)		600-1000	79.8-81.6
6(a)	1371	1000-1600	43-50
6(b)		200-300	45.8-46
7(a)	NA	1200-2000	13.2-15
7(b)		700-1000	15.6-16.1

*Letters in parentheses delineate separate reaches within that particular segment

Then, correlation and regression were used to investigate associations between LWD density and potential controlling factors. A stepwise Poisson regression was used to determine which control variables, of those measured, carried the most influence in explaining LWD density. These statistical analyses were performed on the combined dataset including all segments, and two subsets of that dataset: (1) data within individual segments, and (2) data within specific reaches identified as displaying periodic LWD arrangement within the individual segments (Figure 3.3). These tests were performed on these subdivided datasets because it is likely that geomorphic and riparian controls are longitudinally variable rather than constant, and thus relationships may be more evident when tests are restricted to individual segments, or individual reaches. However, as the data are subdivided, the number of data points, n, are reduced.

For the regression analysis, stepwise Poisson regression was chosen because the format of the response variable (LWD density), count data over a fixed interval of space, more closely satisfies the assumptions of a Poisson distribution, rather than a normal distribution. A Shapiro-Wilk test confirmed that the LWD density data was not normally distributed. One of the key assumptions of Poisson regression is that all observations are independent. It could be argued that LWD density is not necessarily independent, and that wood deposited in one location may affect wood deposition at a nearby location. For this case we are assuming an equilibrated condition in which locations that can store wood already do, and thus have no effect on wood storage upstream or downstream of that location. All statistical analyses were carried out in the open-source software package R. Appendix A contains the R code used in this analysis.

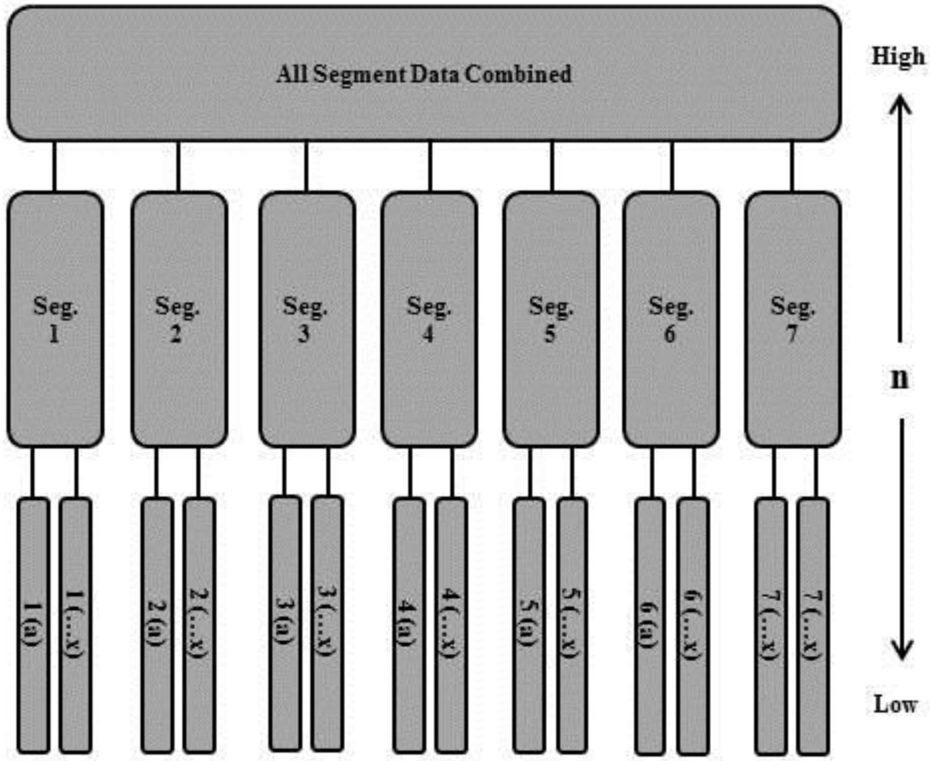

Figure 3.3. This schematic illustrates the experimental design. Statistical tests of association were performed on each of the data subdivisions shown in the schematic above.

3.4. Results and Discussion

3.4.1 *Association of Physical Variables with LWD Periodicity*

Gravel bar spacing and meander wavelength appear to be positively associated with the periodic pattern of LWD density. Table 3.3 displays the segment-averaged variables along with the dominant period identified (Chapter 2).Although only three of the segments studied have a dominant periodic signal associated with LWD density, a strong positive trend is easily identifiable when plotted against bar spacing and meander wavelength (Figure 3.4). This is, of course, interpreted with caution given the strong influence of any one of the three points. Statistically we are unable to verify this relationship, however, theoretically, gravel bars may induce the deposition of wood, or any other material being carried by the flow, because hydraulically, they naturally create a zone of deceleration within the channel. However, field observations indicated that some gravel bars served as wood deposition sites while others did not. Longitudinal patterns of bar formation, and thus bar spacing, is inherently related to meander wavelength (Leopold et al., 1964), therefore the positive relationship between meander wavelength and periodicity is also theoretically feasible. Although discrete controls on periodicity are not statistically evident here, the hint of association with bar spacing and meander wavelength may indicate that they contribute, in some way, to patterns of LWD density.

Table 3.3. Comparison of segment-averaged control variables and dominant period

Segment	Period (m)	Bar Spacing (m)	Meander Wavelength (m)	Segment Sinuosity	Slope
1	348	457	811	1.37	0.00165
5	1071	680	1127	1.19	0.00053
6	1371	844	1538	2.69	0.00023

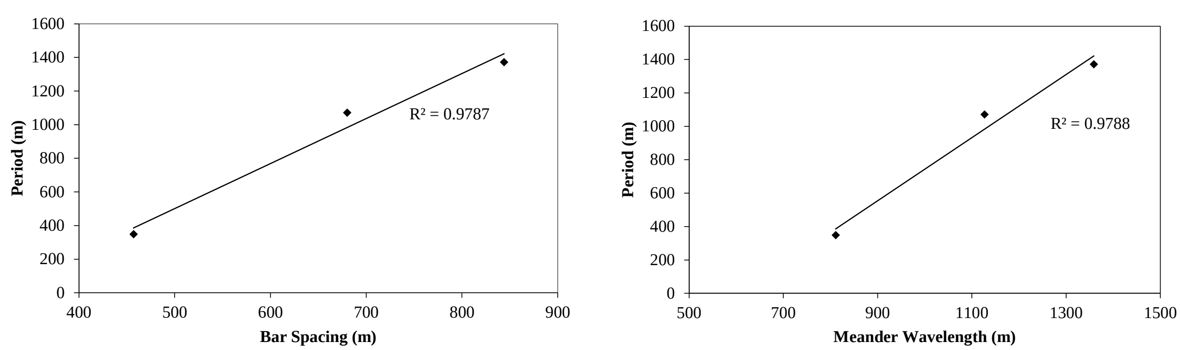

Figure 3.4. Bar spacing and meander wavelength expressed a positive association with period. The period is the longitudinal distance between maximum LWD density.

3.4.2 *Association of Physical and Riparian Variables with LWD Density across Segments*

Kendall τ correlations were performed to investigate relationships between LWD density and possible reach-scale control mechanisms (Table 3.4). The Kendall τ test was used because of the non-normal distribution of the dataset. Although the distribution of the data is less important for the Kendall τ test, we wanted to compare the correlation results with another correlation test, and thus we compared Kendall τ results with Spearman's ρ results. Results were similar, but the Kendall τ test yielded slightly fewer significant results and was thus interpreted to be the more discerning of the two tests. For this reason, the Kendall τ test was used for the remainder of the data analyses.

Table 3.4. Spearman's rho and Kendall tau correlation results for correlation of LWD density with physical and riparian variables using entire dataset. (n=980). Bold represents significant according to the Kendall τ test.

Variable	Spearman's ρ	p-value	Kendall τ	p-value
Channel Width	0.034	0.288	0.024	0.444
Valley Width	-0.004	0.890	-0.004	0.913
Confine. Ratio	-0.015	0.638	-0.011	0.739
Trib. Distance	-0.052	0.101	-0.037	0.248
100m Sinuosity	-0.077	0.016	-0.056	0.078
500m Sinuosity	-0.121	0.000	**-0.089**	**0.005**
1000m Sinuosity	-0.077	0.016	-0.056	0.082
Bar Area	0.010	0.753	0.007	0.824
Drainage Area	0.131	0.000	**0.096**	**0.003**
RB Wood Width	-0.007	0.828	-0.005	0.873
LB Wood Width	-0.099	0.002	**-0.076**	**0.017**
Tot. Width	-0.069	0.031	-0.051	0.114
Elevation	-0.131	0.000	**-0.095**	**0.003**
Slope	-0.014	0.651	-0.010	0.749

When performed across all river segments, the Kendall τ test identified four reach-scale variables as being significantly associated with LWD density: 500-m sinuosity, drainage area, left bank wooded width, and elevation, with p values of 0.005, 0.003, 0.017, and 0.003, respectively. Although significant, the Kendall τ coefficients were quite low, ranging from -0.076 to 0.096, indicating very week relationships. Drainage area and elevation, which are inversely related, displayed the lowest p values and highest Kendall τ coefficients and thus the strongest associations with LWD density. Drainage area displayed a positive association with LWD density, indicating that LWD density increases with increasing drainage area. This relationship is in agreement with the hypotheses suggested by Swanson et al. (1982) and Benda et al. (2003) that wood exhibits increased aggregation in the downstream direction based on assumptions of watershed-position-related source area, transport capacity, and distribution of trapping sites. To test this hypothesis within the context of this research, we compared LWD density between segments with a single-factor ANOVA. Following a square-root transformation of the 100-m density data, the ANOVA revealed significant differences (α=0.05) in mean density between segments. With the exception of segment One, mean 100-m LWD density gradually increases in the downstream direction. Significant increases occur between segments Two and Three, and between segments Four and Five. The boxplot in Figure 3.5 compares the square-root-transformed 100-m LWD densities among segments.

The 500-m sinuosity displayed the next strongest relationship and was negatively correlated with LWD density. This negative relationship is contrary to the assumptions of previously published theoretical models, which suggest straight channels should facilitate efficient movement of wood downstream and more sinuous channels should display higher wood

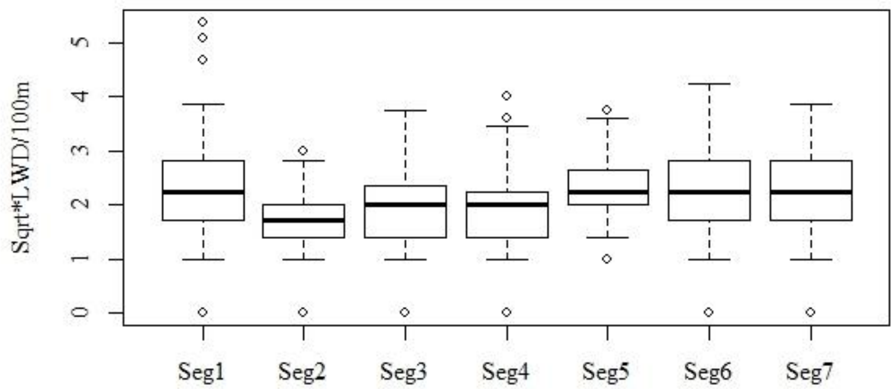

Figure 3.5. Distribution of 100-meter LWD densities among river segments.

densities due to the increased chance of LWD coming into contact with the bank (Swanson, 2003). Additionally, 100-m sinuosity and 1000-m sinuosity, which were not significant at the 95% confidence level but were significant at the 90% level, displayed negative associations with LWD density, indicating that the negative relationship persists even as the scale at which sinuosity is measured changes to incorporate more channel-scale or valley-scale influences on sinuosity.

Stepwise Poisson regression did not yield a statistically significant model relating LWD density to physical variables. The best model that the stepwise procedure could produce included all variables except bar area and tributary distance, and, as such, yielded a residual deviance of 1,809 on 979 degrees of freedom. A chi-square goodness of fit test yielded a p-value of 7.23 e-54, indicating a vast difference between the best fit model, and the ideal model, i.e. a poor fit.

3.4.3 *Association of Physical and Riparian Variables with LWD Density within Segments*

Within-segment Kendall tau correlations revealed statistically significant relationships between LWD density and multiple variables. Although no single variable showed a significant correlation with LWD density across all river segments, valley width was correlated more frequently than any other variable. Table 3.5 displays the results of the Kendall tau correlations in all segments. Segments Three and Seven showed no significant correlations between LWD density and the physical variables tested. The greatest number of significant correlations occurred in segment One, the most upstream segment, and involved correlations with valley width, tributary distance, 500-m sinuosity, bar area, drainage area, and elevation. Also significant were correlations with valley width and confinement ratio in segment Two, with valley width in segment Four, with valley width and elevation in segment Five, and with 100-m sinuosity, 500-m sinuosity, bar area, left bank wooded width, and total wooded width in segment Six.

The step-wise Poisson regression, when applied separately to each of the seven river segments, yielded better results, as compared with the combined segment regression performed across all segments combined. Of the seven segments, regression of data from two segments produced good Poisson model fits, one segment that was very close but not statistically significant, and the remaining four segments yielded poor model fits. Segments Two and Five produced good model fits (Chi square $\alpha = 0.001$), both with five-parameter models. However, what is perhaps more interesting than the good model fits is that the two models with good fit share three of five common variables, as selected by the stepwise regression (Table 3.6): valley width, bar area, and a sinuosity variable: 1000-m sinuosity for segment Two, and 500-m

Table 3.5. Kendall tau results for correlation of LWD density with reach-scale variables within individual segments.

	Segment 1 n = 106		Segment 2 n = 220		Segment 3 n = 221		Segment 4 n = 204		Segment 5 n = 74		Segment 6 n = 94		Segment 7 n = 61	
	τ	**p**	**τ**	**p**	**τ**	**p**	**τ**	**p**	**τ**	**p**	**τ**	**p**	**τ**	**p**
Channel Width	0.034	0.726	-0.022	0.748	0.001	0.988	0.024	0.731	-0.217	0.063	0.040	0.700	-0.034	0.797
Valley Width	0.216	0.026*	-0.179	0.008*	-0.031	0.649	-0.122	0.082**	-0.247	0.034*	0.016	0.877	0.145	0.265
Confinement Ratio	0.085	0.389	-0.115	0.088**	-0.020	0.764	-0.074	0.291	0.038	0.747	-0.030	0.770	0.056	0.667
Trib. Distance	-0.217	0.025*	-0.022	0.742	0.026	0.705	-0.080	0.257	-0.189	0.107	0.040	0.704	0.003	0.979
100m Sinuosity	-0.153	0.118	-0.017	0.800	-0.019	0.775	-0.007	0.925	-0.089	0.452	-0.197	0.057**	-0.152	0.243
500m Sinuosity	-0.290	0.003*	-0.068	0.316	-0.086	0.202	0.022	0.759	-0.160	0.173	-0.176	0.090**	-0.048	0.716
1000m Sinuosity	-0.180	0.065	-0.106	0.118	-0.015	0.827	0.033	0.643	-0.149	0.205	-0.145	0.162	0.120	0.358
Bar Area	0.262	0.007*	0.042	0.537	0.037	0.589	-0.047	0.504	-0.071	0.548	-0.226	0.028*	-0.107	0.412
Drainage Area	-0.378	0.000*	0.090	0.182	-0.037	0.585	-0.078	0.267	-0.190	0.105	0.008	0.940	0.004	0.975
RB Wood Width	0.050	0.613	0.022	0.744	-0.007	0.916	0.017	0.806	0.086	0.469	-0.089	0.396	-0.072	0.580
LB Wood Width	0.083	0.395	-0.105	0.120	0.084	0.216	-0.115	0.102	-0.077	0.515	-0.203	0.049*	0.038	0.769
Tot. Wood Width	0.081	0.408	-0.059	0.381	0.079	0.241	-0.075	0.290	-0.022	0.855	-0.183	0.078**	-0.034	0.793
Elevation	0.373	0.000*	-0.091	0.181	0.040	0.556	0.088	0.213	0.203	0.083**	-0.073	0.486	0.007	0.958
Slope	-0.009	0.930	0.071	0.298	0.029	0.669	-0.062	0.380	-0.004	0.975	-0.160	0.125	0.083	0.527

**Indicates significance at $\alpha = 0.05$*

***Indicates significance at $\alpha = 0.10$*

sinuosity for segment Five. Additionally, the stepwise process for segment Four, which almost produced a good fit, also selected valley width as one of the variables.

Table 3.6. LWD density models for segments yielding acceptable model fits[a,b,c].

Segment	n	Residual Deviance	β_0	β_1	β_2	β_3	β_4	β_5	Chi^2 P-val.
2	219	259.8	2.37	-0.0038 (Cw)	-0.00056 (Vw)	-0.043 (Sin1)	0.000066 (BArea)	-0.0054 (LBw)	0.018
4	204	272.4	3.54	-0.0008 (Ad)	-0.0003 (Vw)	0.006 (RBw)	-0.005 (TOTw)	-0.044 (TDist)	0.0003
5	73	76.1	8.36	0.0946 (CR)	-0.0035 (Vw)	-5.004 (Sin.5)	0.00005 (BArea)	-0.0485 (TDist)	0.233

[a]Poissson regression equation form: $Log_e(Y) = \beta_0+\beta_1 X_1+ \beta_2 X_2$….
[b]Y = LWD Density
[c]Cw=channel width, Vw=valley width, Sin1=1000m sinuosity, BArea=bar area, LBw=left bank wooded width, Ad=drainage area, RBw=right bank wooded width, TOTw=total wooded width, TDist=tributary distance, CR=confinement ratio, Sin.5=500m sinuosity

Although neither test of association revealed a unique controlling variable, the combined results provide evidence of important associations with LWD density. The persistence of valley width as an associated parameter and as a significant contributing predictor variable, along with the larger scales of sinuosity (500-m and 1000-m), directs attention to the larger morphological context of the system. Valley width ultimately confines movement of the channel and exerts influence over other alluvial processes; therefore, in locations where the valley is wide, alluvial processes dominate, and in locations where the valley is narrow, broader-scale geologic controls dominate. The emergence of valley width as an important control of LWD distribution potentially relates to the apparent presence of periodicity in the longitudinal distribution of wood in the Big River.

3.4.4 *Association of Physical and Riparian Variables with LWD Density within Reaches*

The Kendall tau test produced dramatically different results when applied only to the reaches within the segments that had displayed a significant periodic pattern of arrangement. Table 3.7 shows which variables were significantly correlated with LWD density within each reach. Of these, reaches 1(a), 2(b), 3(b), 6(b), and 7(a) had no significant correlations. With the exception of 2(b), the lack of correlations in these reaches is likely to be due to their short reach lengths and thus small sample sizes. At the reach scale, wooded riparian width parameters were [collectively] correlated with LWD density more frequently than any other parameter, followed by the sinuosity parameters. Valley width, the most frequently correlated parameter at the segment scale, was only correlated with LWD density at the reach scale in two of the seven reaches with periodic LWD arrangement patterns.

Stepwise Poisson regression models created for reaches in which periodic patterns of LWD density were identified showed improved performance over segment-specific models. Due to the smaller size of the reaches and the subsequently small sample sizes, regressions could not be performed on reaches 1(a), 3(b), 6(b), and 7(b). However, segments Three, Six, and Seven contained other representative reaches with larger samples with which regressions could be performed. Of the ten reaches for which regressions were performed, eight yielded models of LWD density with an acceptable fit (Chi square $\alpha = 0.001$), and five of those reaches yielded models with substantially better fits than those produced for the segment-specific models (Table 3.8).

Table 3.7. Kendall tau results for correlation of LWD density with reach-scale variables within reaches identified as having a periodic distribution of LWD. Significant correlations between the control variable and LWD density are indicated by an X.

	Segment 2a n = 110	**Segment 3a n = 90**	**Segment 4a n = 80**	**Segment 4b n = 20**	**Segment 4c n = 65**	**Segment 5a n = 20**	**Segment 5b n = 18**	**Segment 6a n = 70**	**Segment 7b n = 6**
Channel Width			X		X				
Valley Width					X				X
Confinement ratio					X				
Trib. Distance					X				
100m Sinuosity						X			X
500m Sinuosity							X		
1000m Sinuosity									X
Bar Area						X			
Drainage Area		X			X	X			
RB Wood Width									
LB Wood Width	X	X						X	
Total Width		X		X					
Elevation		X							
Slope		X							

Table 3.8. LWD density models for reaches yielding acceptable model fits with five or fewer parameters[a,b,c].

Reach	n	Residual Deviance	β_0	β_1	β_2	β_3	β_4	β_5	Chi^2 P
2(a)	106	128.6	5.12	-0.0055 (Cw)	-0.014 (CR)	-3.207 (Sin.1)	0.000084 (BArea)	-0.0065 (LBw)	0.067
4(a)	75	97.9	-1.08	0.004 (Cw)	0.812 (Sin.1)	0.0007 (Ad)	0.007 (RBw)	-0.006 (LBw)	0.039
4(b)	16	8.7	-27.05	24.02 (Sin.1)	4.321 (Sin.5)	-0.00032 (BArea)	-0.0129 (RBw)		0.924
4(c)	43	68.2	1.207	-0.013 (LBw)	0.013 (TOTw)				0.008
5(a)	16	10.2	25.18	-1.225 (TDist)	25.39 (Sin.1)	-21.12 (Sin1)	37.57 (Slp)		0.856

[a]Poissson regression equation form: $Log_e(Y) = \beta_0+\beta_1 X_1+ \beta_2 X_2….$
[b]Y = LWD Density
[c]Independent variables: Cw=channel width, Sin.1=100m sinuosity, Sin.5=500m sinuosity, Sin1=1000m sinuosity, BArea=bar area, LBw=left bank wooded width, RBw=right bank wooded width, Ad=drainage area, TOTw=total wooded width, TDist=tributary distance, CR=confinement ratio, Sin.5=500m sinuosity, Slp=slope

As with the segment-specific models, the stepwise selection of independent variables helps convey the influence of scale on the controls of LWD density. Reach-specific stepwise models included many more of the sinuosity (particularly 100-m sinuosity) parameters and the wooded riparian width parameters (RBw, LBw, TOTw), while concurrently excluding the valley width parameter that had been most prevalent across the segment-specific models. Channel sinuosity and wooded riparian vegetation are both components of processes that operate at much smaller and shorter spatial and temporal scales as compared to valley width. Thus, there would be a greater expectation of finding associations between river system components, such as LWD density, as the analysis scales down to reaches within the larger segments.

3.5. Conclusions

The objective of this research was to identify potential control mechanisms of LWD density and potential control mechanisms of the spatially periodic pattern of fluvial wood density in the Big River. The results suggest that a combination of factors is ultimately responsible for the patterns of LWD arrangement along the Big River and that scale plays an important role in our interpretation of the relationships between LWD density and physical river system parameters. While the interactions of these parameters are indeed complex, our research supports current theories that channel scale (100-m) sinuosity plays an important role in the distribution of fluvial wood within the channel.

No significant relationships were found between segment-scale physical variables and LWD periodicity, however given only the three segments with a strong periodic LWD distribution pattern, positive relationships were acknowledged between periodicity and both meander wavelength and bar spacing. Significant relationships between physical/riparian variables and LWD density were found within individual segments and within reaches previously identified (Chapter 2) as having significant periodic arrangement of LWD. Within river segments, Poisson stepwise regression analyses identified valley width, bar area, and sinuosity as the physical variables that most consistently contributed to the LWD density patterns. Within reaches, the Poisson analyses identified sinuosity and wooded riparian width as key variables. The Poisson stepwise regression produced statistically valid models of LWD density for three of the seven segments and for five of the seven reaches within those segments. The performance of stepwise Poisson regression models was substantially enhanced when the analysis applied only to the reaches in which strong periodicity had been identified. The occurrence of periodically arranged LWD density implies that LWD density is not random in those locations and is thus more influenced by physical/riparian factors. Although valid models were produced, the greatest value of the stepwise regression was in identifying the common variables, of valley width, bar area, and sinuosity at the segment scale, and of sinuosity and wooded riparian width at the reach scale, as consistently contributing to the explanation of patterns of LWD density.

As a confined, meandering, alluvial river, the Big River represents a large number of mid-continent river systems for which very few theoretical or numerical models of LWD dynamics exist. Many models of LWD dynamics have been presented for high-gradient, montane systems and low gradient, alluvial coastal systems; however, they fail to capture the complex interactions that take place at the high gradient/low gradient, confined/unconfined boundaries. Although relationships were variable, and not always strong, this research has demonstrated the influence of valley width on in-channel processes, and thus it's influence on LWD distribution. The varying degrees of valley confinement act as a regulator of smaller-scale alluvial processes. Where the valley is highly confined, fluvial processes are primarily controlled by the valley walls; thus, the regularity of alluvial patterns such as bar spacing, meander wavelength, and sinuosity are disrupted. For example, segment Six of the Big River, with the largest valley widths compared to all other segments, also has the most consistent periodicity in wood arrangement. We infer that this is because the alluvial processes that typically express periodic or cyclical patterns are allowed to function freely without the influence of a confining valley.

In this research, 14 independent variables were investigated as potential controls on wood arrangement, including those identified as being important to the location of LWD in other regions. Future research is likely to benefit from broadening the variety of potential controlling variables beyond those recognized in the current literature. While variables such as channel width are known to affect LWD deposition, our understanding of other variables such as sinuosity is much less clear. From this research we have identified the likelihood that the confined meandering nature of this system affects our ability to apply typical knowledge of alluvial patterns and processes as they relate to LWD dynamics. This research has also highlighted the need for a better understanding of potential controlling variables and the need to include more confined meandering systems in future research on LWD.

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Chapter 4: Reach-Scale Characterization of Fluvial Wood in a Mid-Gradient, Confined-Meander River System

A version of this chapter will be submitted to Applied Geography, for publication by Derek J. Martin, Robert T. Pavlowsky, and Carol P. Harden.

4.1. Abstract

The addition of large woody debris (LWD) to rivers has increasingly become a popular stream restoration strategy, particularly when restoration goals involve enhancing fish habitat and increasing morphological complexity. However, successful application of LWD requires an understanding of the "natural" LWD dynamics within particular types of river systems. This research presents a baseline characterization of LWD within the Big River of East Missouri, a relatively low gradient, semi-confined, alluvial river. For this study, surveys of LWD and channel morphology were conducted at nine reaches along the Big River to investigate relationships between LWD and channel morphometry within the context of similar studies of LWD conducted in other regions. Wood loads in the Big River are low, relative to those of higher gradient river systems of the Pacific Northwest, but high relative to lower-gradient river systems of the Eastern United States. Also, indicator ratios of wood geometry to channel geometry show that the Big River maintains a relatively high wood transport capacity for most of its length. Although LWD creates sites for sediment storage, its overall impact on reach-scale sediment storage in the Big River is low. Data generated from this study can serve as a baseline against which other Midwestern LWD studies can be compared. These comparisons will be necessary to better understand LWD dynamics in Midwestern rivers and to successfully integrate LWD into restoration and management plans.

4.2. Introduction

Large woody debris (LWD) is universally recognized as an important ecological and geomorphological component of river systems. However, the role of LWD in river systems differs depending on region, climate, and landuse history (Gregory et al., 2003). Motivations for understanding the dynamics of fluvial wood have traditionally been rooted in fish ecology (Murphy et al., 1984; Bisson et al., 1988; Beechie and Sibley, 1997; Naiman et al., 2000); however, researchers have recently come to understand the broader diversity of roles that LWD serves in river systems, from bank stabilization (Mott, 1994; Abbe et al., 1997; Derrick, 1997; Brooks, 2001; Shields et al., 2004), to biogeochemical cycling (Bilby and Likens, 1980; Benke et al., 1985, Bilby, 2003) and sediment regulation (Potts and Anderson, 1990; Diehl, 1997; Wallerstein et al., 1997; Downs and Simon, 2001; Montgomery et al., 2003). While rivers in the Pacific Northwest and numerous other coastal and montane regions have been the focus of a majority of these studies, LWD in streams of the Midwestern United States and other physiographically similar regions have been given far less attention. However, stream restoration projects involving the use of LWD are becoming increasingly common in the Midwest region (Alexander and Allen, 2006).

Alexander and Allen (2006) conducted a comprehensive study of stream restoration projects that have taken place in the Upper Midwest of the United States between 1970 and 2004. They found that, of 1,345 stream restoration projects, in-stream habitat improvement and bank stabilization were the two most common restoration goals. Of the 20 most popular procedures implemented to accomplish those goals, the addition of LWD to the river channel was the third most used. Besides the discrete addition of LWD as a restoration tool, five of the remaining 19 procedures involved wood in some way. Alexander and Allen (2006) did not specifically address the success rates of the restoration projects or the LWD application. Their results support the common sentiment that stream restoration projects lack adequate pre- and post- project monitoring, particularly those involving LWD (Reich et al., 2003). Furthermore, Abbe and Montgomery (2003) found that the majority of restoration projects involving the reintroduction of LWD to a system have been heavily based on subjective decisions and that guidelines for such projects do not provide natural analogs for wood placement. A baseline understanding of contemporary wood loads is thus necessary for successful application of LWD as a restoration tool. This baseline has been relatively well established for river systems of the Pacific Northwest of the United States, but is lacking for lower gradient Midwestern river systems.

To establish a baseline understanding of reach-scale LWD distribution, abundance, and geomorphic role in a mid- to low-gradient Midwestern river system, we conducted comprehensive LWD surveys at nine locations along the main stem of Missouri’s Big River, from its relatively high-gradient, upper portion to its confluence with the Meramec River, 210 km downstream (Figure 4.1). We used these data to address the following questions: (1) what are the contemporary wood loads within the bankfull channel of the Big River; (2) do wood loads vary longitudinally in the Big River; (3) to what extent is LWD responsible for reach-scale sediment storage; (4) are LWD characteristics (length, width, volume, orientation) related to volume of sediment stored; and (5) is the size of sediment stored related to the characteristics of the LWD? The overarching goals of this research are to develop a baseline understanding of contemporary wood loads in a Midwestern river system, contribute to the wider understanding of LWD's role as a geomorphic agent in Midwestern rivers, and provide further insight into the complex sediment dynamics of a river system plagued with a highly contaminated sediment load.

4.3. Study Area

4.3.1 *Geologic and Geomorphic Setting*

The Big River is located in the Ozarks physiographic region and is influenced by a wide variety of surficial geology (Figure 1). The headwaters of the Big River initiate in the St. Francois Mountains, which are an expression of the igneous core of the wider Ozarks uplift. The remainder of the river system is primarily underlain by dolomite-limestone and shale units. As a result, the Big River is highly influenced by karst processes. The Big River contributes to the deeply dissected nature of the Ozarks uplift as it drops nearly 100 meters from its headwaters to the confluence.

4.3.2 *Landuse History*

Most LWD research has occurred in montane regions, in watersheds that support relatively old riparian forests. The Big River drains a watershed with a substantially different land use history that has resulted in narrower wooded riparian corridors and comparatively younger riparian forests. The Ozarks Region has undergone multiple stages of settlement and land use since the early 1800s (Rafferty, 1980). The first stage of settlement occurred between

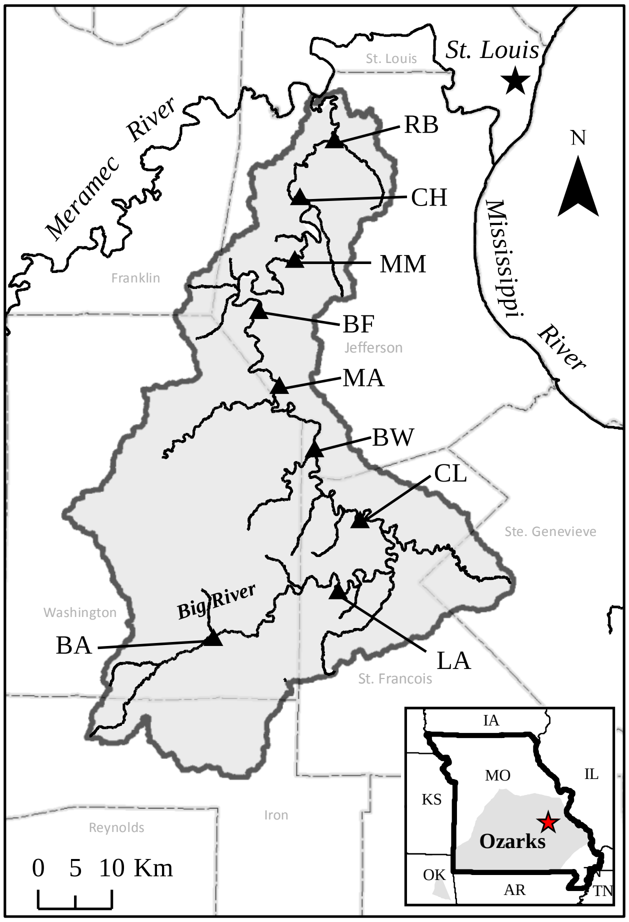

Figure 4.1. Map of the Big River, tributaries, associated watershed, and locations of the nine study reaches.

1800 and 1850 when mostly French Creoles began to settle the eastern Ozarks after the discovery of numerous mineral commodities. The second wave of settlement occurred from about 1850 to the early 1900s as a result of post-Civil War reconstruction. During this time, railroads penetrated the interior of the Ozarks and widespread settlement closely followed. One of the most productive lumber companies in the country was being operated in the central Ozarks region during this time period. However, by the early 1900s, much of the region had been completely depleted of commercially viable lumber. Along with, and then following, the widespread timber harvest, agriculture took over as the most dominant land use in the Ozarks. It has been suggested that the widespread land clearing that occurred in the Ozarks region is responsible for the contemporary sediment loads in Ozark Rivers, which consist primarily of chert gravel (Saucier, 1983; Jacobson and Prim, 1994; Jacobson and Gran, 1999; Panfil and Jacobson, 2001; Jacobson, 2004). Land clearing for timber harvest and agriculture also included clearing of the riparian forests, and in most cases resulted in complete removal of riparian trees. Consequently, contemporary riparian forests are relatively young in age.

4.3.3 *Mining History*

The Big River drains what is known as "the Old Lead Belt." The Old Lead Belt is a sub-district of the larger Southeast Missouri Lead Mining District, which was a national leader in the production of lead and zinc ore between 1869 and 1972 (Pavlowsky, 2010). Much of the mine waste material, or chat, still remains in the form of large chat piles. The highly contaminated chat material now makes up a relatively substantial portion of the Big River's bed load. In 1992, portions of the Big River watershed were listed on EPA's Superfund National Priorities List for lead contamination after studies revealed numerous adverse human health impacts (Asberry, 1997; Gunter, 2011). Additionally, impacts to wildlife range from reduced abundance, diversity, and density of freshwater mussels (Buchanan, 1979; Schmitt et al., 1987; Roberts and Bruenderman, 2000; Roberts et al., 2009) to elevated levels of lead in crayfish (Allert et al., 2010) and other fish, resulting in fish consumption advisories along the Big River (MDHSS, 2011). The LWD study presented here is part of a larger effort to understand the dynamics of contaminated sediment in the Big River by investigating the extent to which LWD stores fluvial sediments.

4.4. Methods

For this research, an LWD inventory was taken along nine reaches of the Big River, varying in length from 0.2 to 0.7 km, over the course of two field expeditions conducted between August 2012 and May 2013. Eight of the nine reaches correspond to reaches in which topographic surveys had been performed and sediment sampled previously to support lead-contamination research (Pavlowsky et al., 2010). For the purposes of this research, LWD was identified as any unattached piece of wood within the bankfull channel that was ≥ 1.0 m in length and ≥ 0.10 m in width. The location of each piece of LWD was recorded with a global positioning system (GPS) unit, along with a variety of LWD characteristics and associated sediment characteristics (See Appendix C for an example of the field worksheet). Topographic channel surveys were also conducted along the entire length of each of the study reaches. Much of the topographic survey data was supplied by the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University, the same institute that had previously conducted the lead mining sediment contamination research. New topographic surveys conducted during the 2013 field expedition followed the method used by Pavlowsky et al. (2010).

We measured the length, width, and orientation of each piece of wood in each of the nine reaches using a combination of methods adapted from Magiligan et al. (2008), Pavlowsky and

Martin (2010), and Wohl (2009). Three width measurements, one at each end of the piece and one in the middle, were taken and averaged. The average width was then used, along with length, to calculate the LWD piece volume, using the standard formula for the volume of a cylinder (Eq. 1). Width measurements for each piece were averaged to help satisfy the assumption that the LWD is a uniform cylinder. The angular orientation of each piece of wood relative to the bank was also documented (Figure 4.2).

Piece Volume (m^3) = $\Pi r^2 h$ (Eq. 1)

π is approximately 3.142
r is the radius of the LWD (1/2 width in meters)
h height of the cylinder (length of the LWD in meters)

We also measured the length, width, and height of every woody debris jam. To be considered a jam, at least three pieces of LWD had to be collected on a key member, a larger piece of wood that serves as an anchoring piece on which others collect (Abbe and Montgomery, 2003). LWD jam volume was calculated by multiplying the width, depth, and height of the jam. In some cases, individual trees with intact rootwads were responsible for forming jams at their rootwad ends. In these cases, the rootwad jam was measured as a jam and then the trunk of the tree was measured as an individual piece of LWD to more accurately reflect the true LWD volume.

Wood-induced sediment deposits were also characterized within each study reach. If pieces or jams were visually interpreted as being responsible for storing sediment, the geometry of the deposit was measured to calculate the volume of the deposit. To do this, a sediment probe was pushed through the deposit until a refusal depth was reached (Lisle and Hilton, 2007). Refusal, the point at which the probe can no longer penetrate the sediment, was assumed to be the contact between deposited sediment and the coarse channel lag. Thus, the depth of refusal was measured as the depth of deposited sediment. Three probe depths were recorded along the longest axis of the deposit and sediment samples were collected at each of the sediment probe locations for a later laboratory determination of the size characteristics of sediment in the LWD-induced deposit.

Particle-size distribution was determined for each sample using a dry-sieving method. Sediment samples were dried in an oven at 60^{o} Celsius for at least 24 hours. Samples were then weighed, disaggregated if necessary, and poured through a sieve stack that was then placed on a sieve shaker for five minutes. Sample proportions retained on each sieve were then weighed to develop a particle-size distribution for each sample. Sieve sizes (8 mm, 4 mm, 2 mm, 1 mm, 0.5 mm, and 0.08 mm) were chosen based on a combination of (1) common particle-size categories (Wentworth, 1922) and (2) particle sizes associated with the stages of processing during the lead mining process (Taggart, 1945 in Pavlowsky et al., 2010), which would help identify sediment storage potentially linked to the mining sediments.

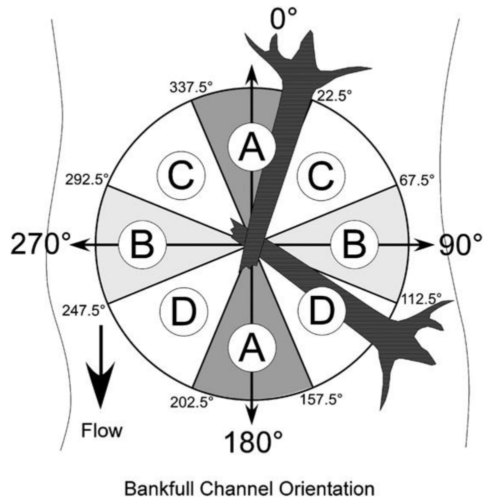

Figure 4.2. Orientation of LWD by zone. Adapted from Schuett-Hames (1999) cited in Magilligan et al.(2008).

We tested for statistically significant associations between channel geomorphic variables and LWD characteristics, as well as for associations between LWD characteristics and sediment storage characteristics. Topographic surveys performed at each study reach provided measurements of channel width, channel depth, cross-sectional area, and slope. We tested whether these variables were associated with LWD size characteristics using Spearman correlation. We also used Spearman correlation to test for associations between LWD characteristics, including LWD piece angle, and sediment size characteristics. Additionally, sediment storage related to LWD was compared to in-channel storage estimates made from previous channel surveys (Pavlowsky et al., 2010).

4.5. Results and Discussion

4.5.1 *Characteristics of Contemporary Wood Loads in the Big River*

Surveys of all nine study reaches yielded a dataset consisting of 242 pieces and 49 jams over a combined 4 km of the Big River (Table 4.1). Figure 4.3 displays the proportion of LWD jams to LWD pieces and their downstream variation among the nine reaches surveyed. The number of jams per reach is extremely variable and lacks an obvious downstream trend; however, the number of LWD pieces per reach slightly increases in the downstream direction. Furthermore, the number of pieces exceeding 20 cm in diameter also increases in the downstream direction (Figure 4.4). The increase in pieces exceeding 20 cm in diameter may likely be attributed to the increasing prevalence of channel widening and bank erosion in downstream reaches. Field observations indicated that the frequency and magnitude of eroding banks increased in the downstream direction. In many locations, channel widening appeared to be the dominant form of wood recruitment to the channel, often resulting in the recruitment of large trees to the channel.

Table 4.1. Reach-specific LWD characteristics.

	Reach	Length (km)	Pieces	Jams	Total Vol. (m^3)	Pieces/100 m	Jams/100 m
Upstream	BA	0.2	14	3	26.2	7	2
	LWA	0.6	23	7	558.1	4	1
	CL	0.6	28	6	39.2	5	1
	BW	0.3	23	10	343.1	8	3
Downstream	MA	0.4	18	4	199.8	5	1
	BFA	0.4	43	4	380.0	11	1
	MM	0.6	37	7	132.1	6	1
	CH	0.4	22	1	12.97	6	0
	RBA	0.4	34	7	155.1	9	2

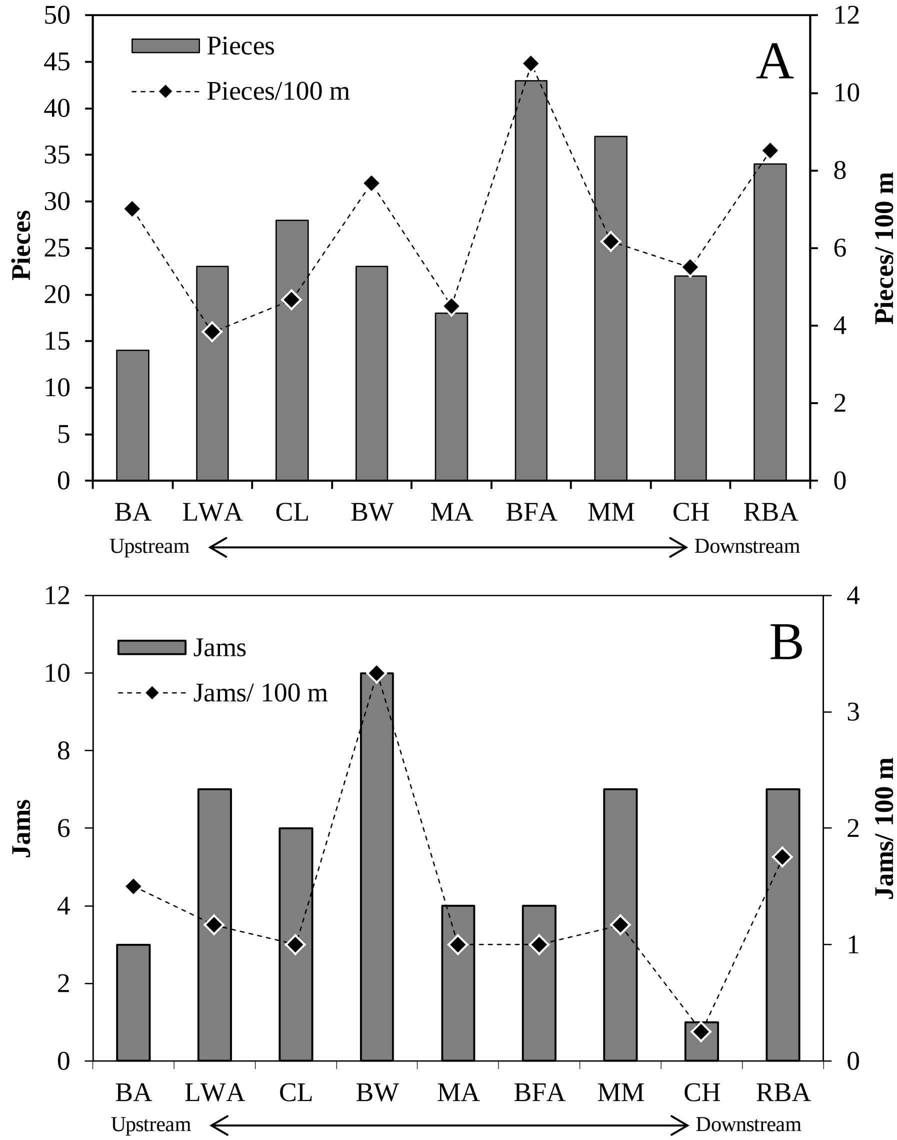

Figure 4.3. Downstream variation in (A) LWD pieces and (B) LWD jams.

In general, the amount of LWD within the bankfull channel was lower than expected. However, overall wood loads were high relative to those reported in other studies conducted in the Eastern and Midwestern United States (Benda et al., 2003; Gurnell, 2003; Magilligan et al. 2008) and low relative to those reported in the Western United States (Gurnell, 2003). Reach-

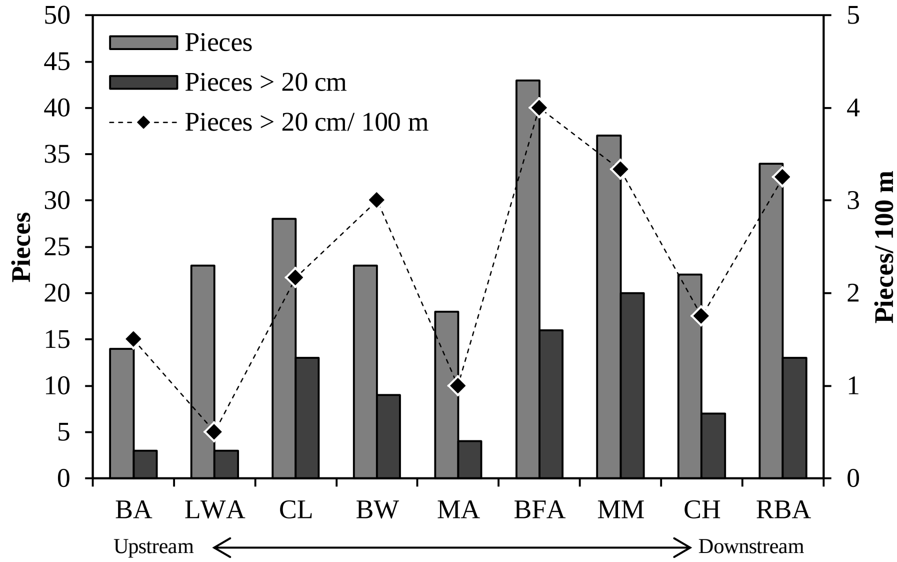

Figure 4.4. Downstream variation in LWD pieces greater than 20 cm in diameter.

specific wood loads were extremely variable; thus, no downstream trend in wood loading was identified (Figure 4.5). Jams accounted for a much larger portion of the total wood load than pieces. On average, jams accounted for nearly 83% of the total wood volume per reach, ranging from 99.5% of the total volume in LWA, to 19.2% in CH. Although other studies of low-gradient systems lack comparable measurements of jam volume, they have demonstrated that the frequency of jams in other systems is quite low (~ 1 per km, Magilligan et al., 2008) relative to the average of 17 jams per km within the Big River. However, comparisons are approached with caution because criteria for designating a jam vary by study. However, jam frequency could be an indicator of LWD supply, indicating that other systems are perhaps more supply-limited than the Big River.

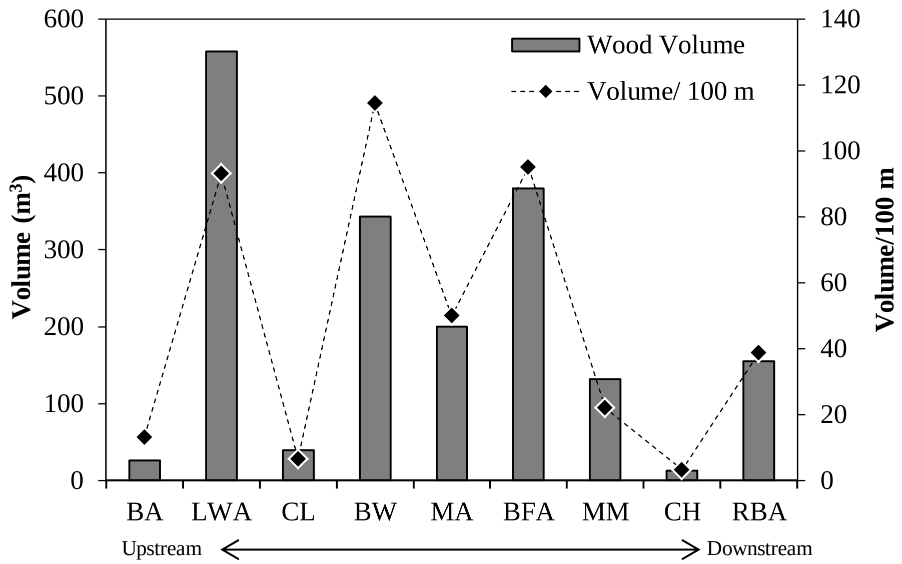

Figure 4.5. Downstream variation in wood volume in the Big River, Missouri.

Wood accumulations classified as jams in the channel of the Big River were often difficult to measure by following the procedures common in the LWD literature because the structure of a typical jam in the Big River differs substantially than that of jams in coastal and montane systems. Although technically classified as such, LWD jams in the Big River often contained a relatively high proportion of open space, lacking the large accumulations of smaller organic debris common in other systems (Figure 4.6). Therefore, wood volumes calculated for jams in the Big River are likely to overestimate the true wood volume occupied by the jam. The aforementioned difficulties in measuring volume and comparing frequencies bolsters the call for common LWD metrics and region-specific criteria as set forth by Wohl et al. (2010).

Figure 4.6. Photograph showing a typical in-channel accumulation of wood in the Big River, classified as a jam.

In general, the physical dimensions of LWD were consistent across reaches, averaging between 2.7 and 4.9 m in length and between 12 and 24 cm in width (Figure 4.7). The maximum piece length was 31.8 m, and the maximum width was 300 cm. The LWD pieces in the Big River are large relative to those documented in other regions by recent studies (Table 4.2) and, although river systems in different regions support different woody riparian species and ecosystems, insights can be drawn from their comparison. Observations of the Big River's larger LWD sizes support the previous conjecture of recruitment processes being primarily related to bank erosion, as opposed to tree mortality. The other studies presented in Table 4.2 represent much older riparian forests. The larger size of the trees in older-growth forests are much more prone to breakage by windthrow, which would result in more, smaller pieces being recruited to the channel, as opposed to whole trees. In the Big River, if bank erosion is the primary recruitment process, there is a greater likelihood of entire trees being recruited to the channel, as opposed to just pieces of larger trees. Additionally, many of those other systems are subject to additional recruitment processes that are not as common in the Big River, such as landslides, which carry not only whole trees into the channel, but also all of the other downed wood and organic debris that occupies the riparian forest floor.

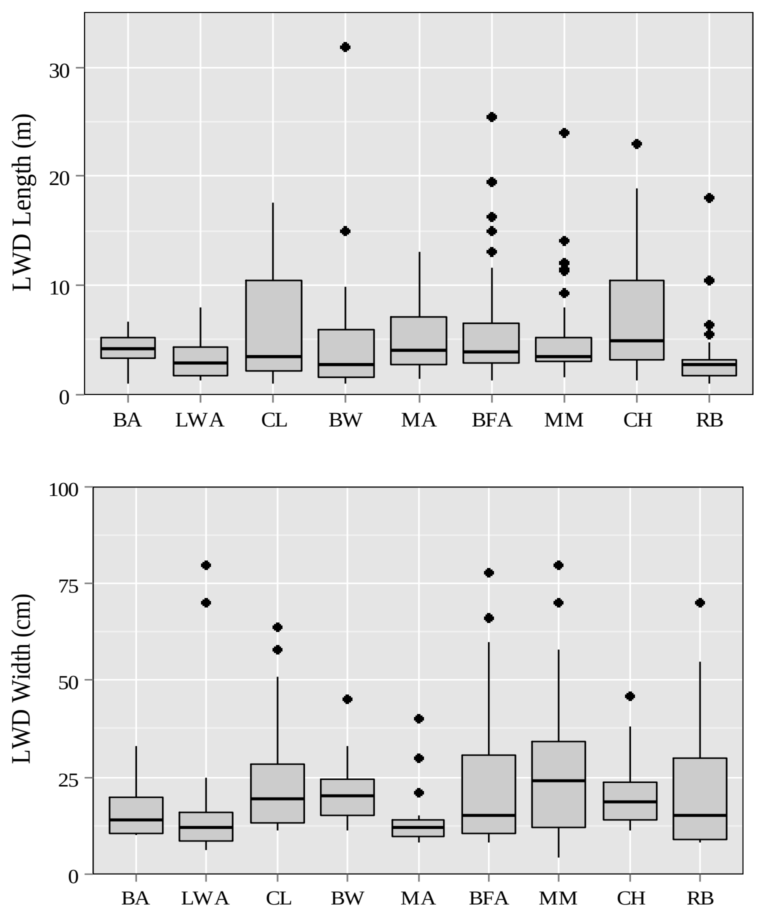

Figure 4.7. Box plots comparing (A) LWD piece length and (B) piece width in nine reaches of the Big River. The Y-axis of piece width has been truncated. An outlier of 300 cm (not shown) occurs in BW.

Table 4.2. LWD size characteristics from five different regions and their relationship with channel parameters, which are indicative of relative wood transport capacity.

Site	W^a (m)	Wood L_{avg}[b] (cm)	Wood d_{avg}[c] (cm)	L_{avg}/W[d]	d_{avg}/flow depth[e]	Reference
Colorado Front Range, USA	5-17	250	19.5	0.31 (0.09-1.27)	0.28 (0.08-1.32)	Wohl, 2011
La Selva, Costa Rica	3-15	395	18.8	0.62 (0.23-1.85)	0.35 (0.13-1.13)	Wohl, 2011
Congaree NP, S. Carolina, USA	8-13	334	21.7	0.30 (0.19-0.40)	0.07 (0.06-0.08)	Wohl, 2011
Coastal Maine, USA	10-54	565	19.2		0.14 (0.06-0.31)	Magilligan et al. 2008
Big River, Missouri, USA	7-57	511	22.7	0.13 (0.02-0.88)	0.15 (0.03-2.34)	This study

[a] W is bankfull channel width; range of values for different channel segments surveyed.
[b] Wood L_{avg} is average wood piece length.
[c] Wood d_{avg} is average wood piece diameter.
[d] L_{avg}/W is the ratio of average wood piece length to channel width; average for all channel segments surveyed, followed by range in parentheses.
[e] d_{avg}/flow depth is ratio of average wood piece diameter to bankfull flow depth; average for all channel segments surveyed, followed by range in parentheses.

A majority (56%) of the LWD pieces in the Big River were oriented in the A-position (parallel to the direction of flow, 0° to 22.5° relative to the bank) (Figure 4.8). Field observations suggest that this orientation can, in most cases, be attributed to imbrication of the wood. This orientation is also an indication of the wood transport capacity of the river system. Low transport capacity would result in fewer pieces mobilized and thus fewer pieces imbricated. It may also be a reflection of the dominant recruitment process of bank erosion because many trees that are recruited through bank erosion will remain, at least for a short time, attached to the bank, with the root system serving as a pivot point from which the flow reorients the tree in the downstream direction. The second most common (23%) orientation was the C orientation, which represents the 22.5° to 67.5° angle relative to the bank, followed by the B orientation (13%), and the D orientation (8%). Angles of orientation were investigated further as a potential factor controlling wood-related sediment deposition, and are discussed later.

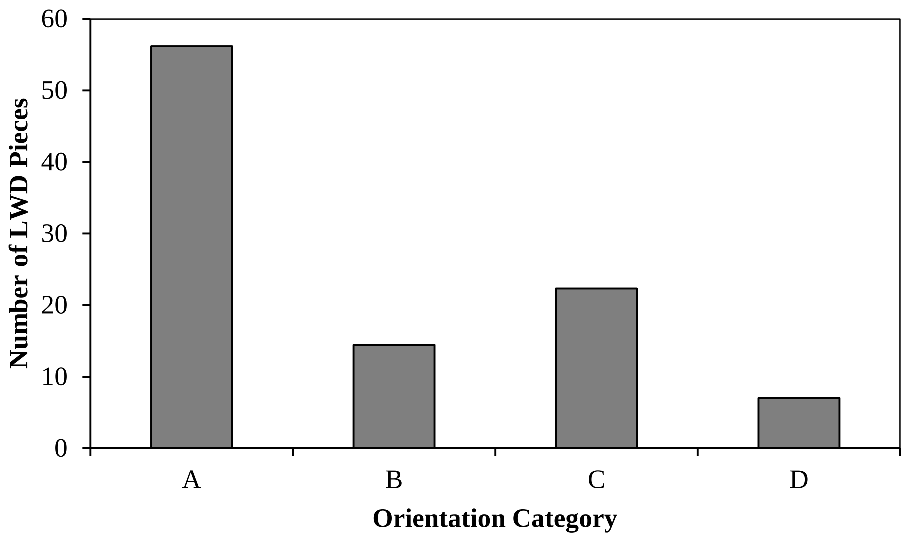

Figure 4.8. Spatial orientation of LWD pieces in the Big River by percent of total pieces.

4.5.2 *Associations between LWD and Channel Characteristics*

Correlation analyses revealed no significant relationships between individual LWD characteristics and channel characteristics in the Big River. Additionally, channel characteristics measured were poor predictors of the spatial distribution of LWD along the reaches. However, the relationships between piece length and channel width, and between piece width and channel depth, within each of the study reaches provides valuable comparisons of wood transport capacity at different locations along the river network and allow comparisons with the other studies outlined in Table 4.2.

Overall, LWD transport capacity in the Big River is high relative to that of the other systems represented in Table 4.2. The relatively low piece length to channel width (L_{avg}/W = 0.13) ratio and piece diameter to flow depth (d_{avg}/flow depth = 0.15) ratio, averaged for the nine reaches studied in the Big River, indicate that, relative to other systems studied, there is a much greater likelihood that LWD will undergo fluvial transport in the Big River. Initially, this would have been expected, given that the range of drainage areas sampled in the Big River far exceeds the areas of many of the other studies included in Table 4.2; however, given the larger sizes of LWD pieces in the Big River, the ratios are somewhat scaled, and thus comparable. When the ratios are calculated for each individual reach, as opposed to being averaged over all the reaches, they show (Figure 4.9) a slight decrease in the downstream direction, which would be expected as the channel widens and deepens; but, the downstream variations in wood size help to moderate the downstream variability of the ratios. The ratios at BA, the reach with channel widths and drainage areas most comparable to those in Table 4.2, are still low compared to those reported by Wohl (2011). Even at the farthest upstream reach studied on the Big River, wood transport capacity remains relatively high.

4.5.3 *LWD-Related Sediment Storage*

Overall, sediment storage related to LWD in each reach is low. In general, the percentage of LWD pieces responsible for storing sediment decreased in the downstream direction, with the highest percentage (23.3%) occurring at LWA, the second farthest upstream reach, and the lowest percentage (4.3%) occurring at CH, the second farthest downstream reach (Figure 4.10). More than half (68%) of all LWD pieces responsible for storing sediment were in jams.

However, there was no difference between piece-related and jam-related sediment storage volume ($\alpha = 0.01$).

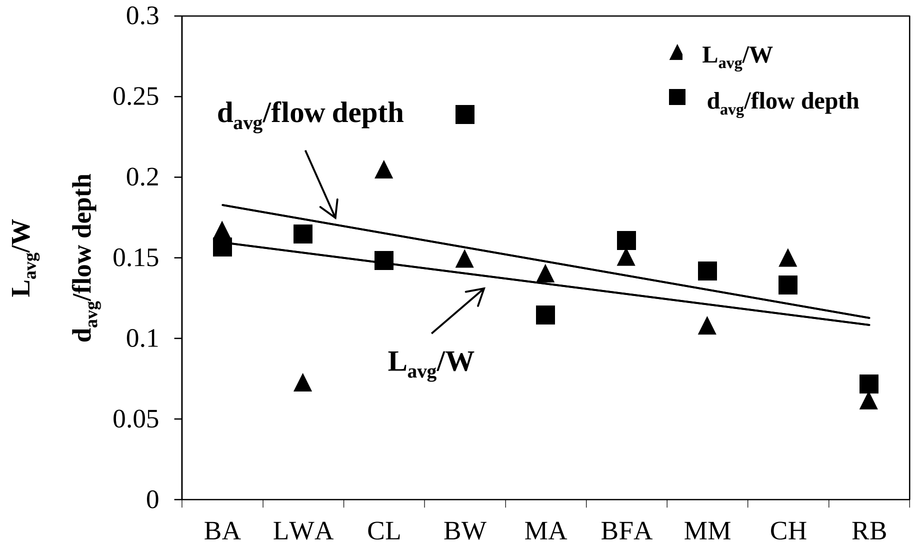

Figure 4.9. Downstream variation in LWD transport capacity indicators in nine reaches of the Big River. L_{avg}/W represents the ratio of average piece length to channel width, and d_{avg}/flow depth represents the ratio of average piece diameter to flow depth.

The volume of sediment stored by LWD is extremely variable and does not display a discernable downstream trend (Figure 4.11). The LWA reach and the BFA (farther downstream) reach had substantially more LWD-related sediment storage compared to the other reaches, with 39.2 m^3/100 m and 69.5 m^3/100 m of sediment storage, respectively. LWD was responsible for a relatively small percentage of in-channel sediment storage at most reaches when compared to prior estimates of in-channel, reach-scale sediment storage determined by Pavlowsky et al. (2010). The percent of in-channel sediment storage attributed to LWD ranged from 0.06 % in the BW reach to 4.2 % in the BFA reach. Although the BFA reach was the only reach that had more than 50 m^3 of LWD-related storage, it demonstrates that LWD does have the potential to store significant amounts of sediment in this particular type of system.

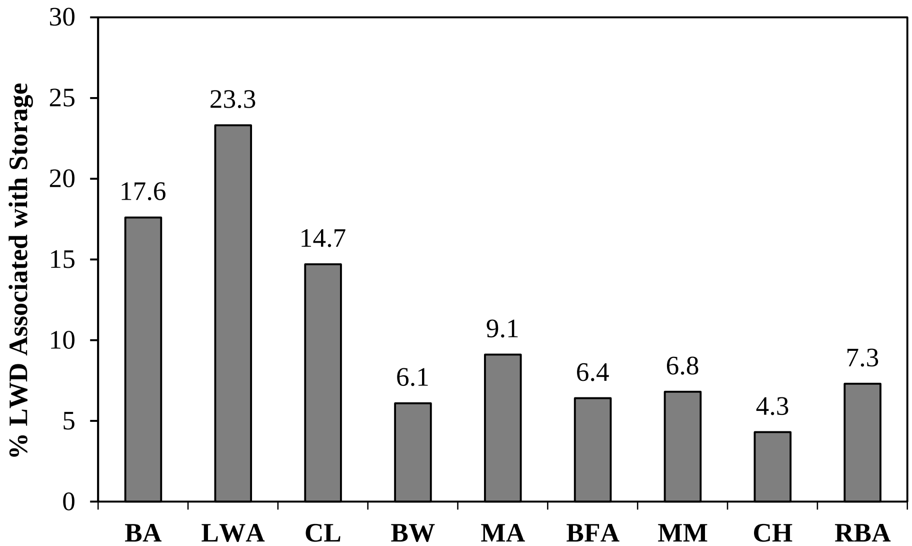

Figure 4.10. Bar graph showing the percentage of LWD associated with sediment storage in each of the nine studied reaches of the Big River.

4.5.4 *Association between LWD and Sediment Characteristics*

Although LWD characteristics were poor predictors of sediment volume, LWD pieces with the categorical orientation of B (perpendicular to the flow) tended to store larger volumes of sediments than those in other orientations (Table 4.3). This is expected, as pieces oriented perpendicular to the flow can have the greatest hydraulic impact. Should they become stabilized in this position, pieces of wood perpendicular to the flow create a damming effect, whereby sediment is deposited upstream of the piece, as well as downstream. This was the case with one piece, BF-P11 at the BFA site, which had the highest percentage of LWD-related in-channel storage compared to the other reaches (Table 4.3). However, as previously noted, this particular orientation was infrequent because, in most cases, the consistently high transport capacity of the channel is likely to orient pieces more parallel to the channel.

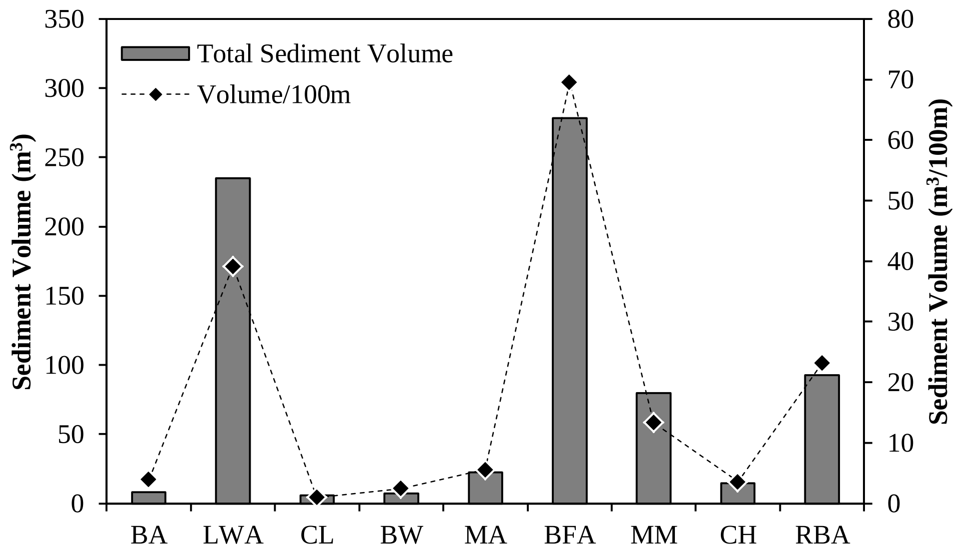

Figure 4.11. Volume of sediment stored by LWD in each of the nine studied reaches of the Big River.

Table 4.3. Characteristics of LWD pieces responsible for storing sediment among the nine reaches studied in the Big River, Missouri.

Piece ID	Length (m)	Width (cm)	Piece Vol. (m^3)	Orient.	Sediment Vol. (m^3)
BA-RP2	3.97	22	0.15	A	4.5
BA-LP1	1.2	10	0.21	A	1.0
LA-P14	2	70	0.77	C	9.3
CL-LP3	10.49	51	2.14	C	0.8
CL-LP4	2.4	23	0.10	C	0.2
CL-LP6	11.3	48	2.04	A	1.1
CL-LP7	1.02	13	0.01	B	1.0
BF-P11 (US)	10.8	34	0.98	B	80.6
BF-P11 (DS)	10.8	34	0.98	B	33.3
BF-P25	6.1	31	0.46	C	33.3
CH-RP1	15.3	38	1.73	D	14.4

LWD characteristics, including orientation, were also poor predictors of sediment size characteristics. LWD-related sediment size distributions were extremely variable among study reaches and among individual pieces and jams. Overall, LWD tended to store more fine sand (0.08 mm) and medium gravel (4 to 8 mm) compared to other sediment sizes (Figure 4.12). Sediments within these particle-size ranges typically make up about one quarter to one half of the total bed load in Ozark streams, the remainder of which typically consists of large gravels and small cobbles (Pavlowsky and Martin, 2009) and thus, it appears that LWD has little effect on the sorting of sediments in the Big River. Additionally, the 4 to 8 mm and 0.08 mm particle-size fractions correspond to the size fractions of the lead mining-related waste products in the channel of the Big River known as “chat” and fine “tailings,” which have been identified as being contaminated (Pavlowsky et al., 2010). The large volumes of chat and tailings in the Big River from the mining influence in the region make it likely for these size fractions to occur more frequently than others in LWD-related sediment deposits. The presence of sediment from lead mining would explain differences in the sizes of sediment stored in two contrasting reaches. Sediment stored by LWD at CL, located downstream of the mining-impacted drainage area, clearly contains larger proportions of chat and tailings-sized sediments compared to sediment stored by LWD at BA, located upstream of the mining-impacted drainage area (Figure 4.13).

4.6 Conclusions

Overall, contemporary wood loads in Missouri’s Big River are low, compared to those in montane systems, and slightly high, compared to other recently studied low-gradient river systems. The Big River represents a physiographic setting that has not previously been described in the fluvial wood literature. Data for the Big River, derived in this research, thus provide a baseline for future comparisons of fluvial wood loads in other mid to low-gradient Midwestern river systems, and in river systems with semi-confined, alluvial morphologies.

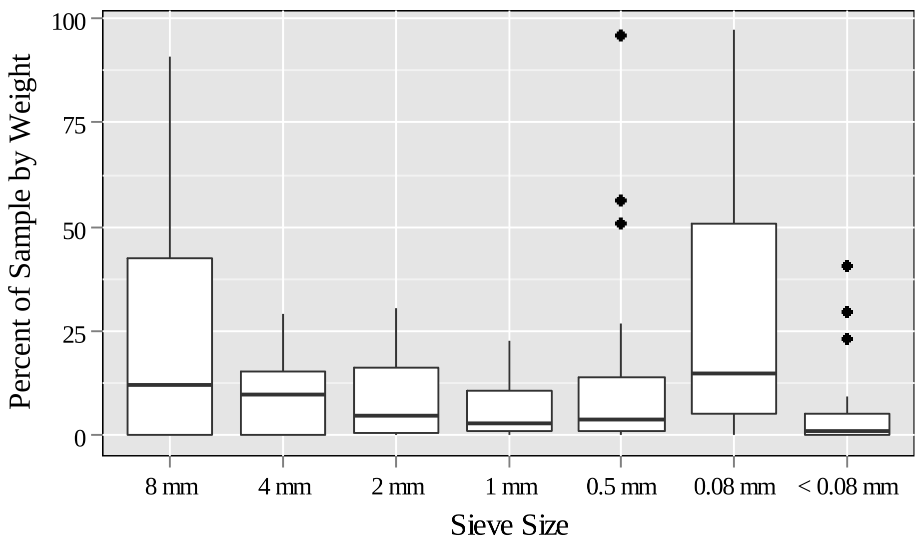

Figure 4.12. Box plot comparison of particle-size distributions for all LWD-associated sediment samples combined.

This research has demonstrated that LWD plays a minimal role in the storage of sediment in the Big River relative to current in-channel storage volumes. However, this research has also demonstrated that LWD has the potential to store relatively substantial amounts of sediment in the Big River given certain conditions, as exemplified by the BFA study reach. Although no relationships were identified between the LWD metrics and sediment metrics, LWD-induced sediment deposits were found to contain a similar range of particle sizes as the typical bed-load, suggesting that, within the context of this river system, LWD does not alter flow conditions enough to induce sorting. Additionally, we have demonstrated that wood dynamics in the Big River differ from those in other regions. In particular, the Big River maintains a relatively high wood transport capacity for most of its length, even in the farthest upstream reaches. The long piece length of wood in the Big River leads us to suggest that the primary recruitment mechanism along the river is by bank erosion and channel widening, not by tree mortality or mass movements, as observed in numerous other studies.

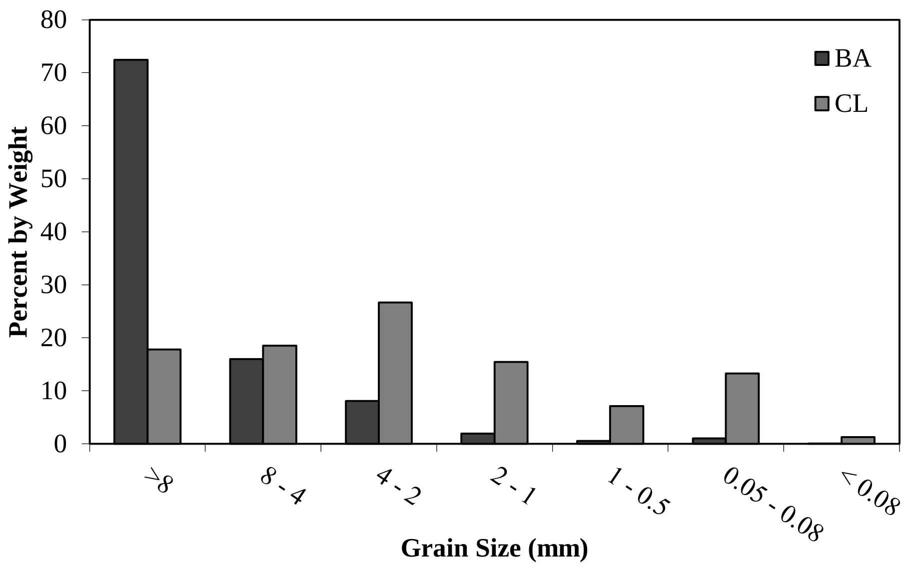

Figure 4.13. Site-averaged particle-size distributions for LWD-stored sediment in reach BA, located upstream of the mining areas, and reach CL, located just downstream of the mining areas.

Due to the increasing popularity of riparian forest management in the Midwest in recent decades, riparian forests are likely to reach ages that are unprecedented during the last 150 years. As a result, Midwestern river systems are likely to experience increases in wood loads as more trees reach common mortality age. Additionally, the introduction of disease and invasive insect species, such as the emerald ash borer, are also likely to have great impacts on riparian tree mortality and consequently, in-stream wood loads. Thus, it is imperative that we understand the complex dynamics of LWD in Midwestern river systems. Stream restoration efforts in the Midwest will greatly benefit from an enhanced understanding of fluvial wood dynamics in river systems like the Big River.

4.7 Acknowledgements

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Chapter 5: Summary and Conclusions

5.1. Conclusions

The purpose of this dissertation research was to investigate geomorphic and riparian controls on the arrangement of LWD within the Big River of East Missouri, and to provide a baseline, reach-scale characterization of LWD within this semi-confined, Midwestern river system. This research begins to fill an important regional gap in our understanding of fluvial wood dynamics by demonstrating key differences between LWD dynamics in the Big River and in river systems for which we already have a good understanding of fluvial wood dynamics. Additionally, this research demonstrates the importance of using a multi-scale approach to gain a more holistic understanding of LWD-related fluvial processes. This knowledge is imperative, as stream restoration projects in the Midwest increasingly involve the addition of LWD in some capacity, and as fluvial wood loads in Midwestern rivers are likely to increase in the future. In this chapter, I summarize the major conclusions that I have drawn from this research and provide recommendations for future research.

1) Longitudinal patterns of LWD arrangement are not random in the Big River.

By analyzing LWD density at 100-m intervals along nearly one fourth of the entire main stem of the Big River, my research has shown that LWD arrangement is not random and that it exhibits a tendency toward clustering. Local and global Moran's I analysis of spatial autocorrelation identified that 100-m LWD density was autocorrelated within each of the nine inventoried river segments. The Global Moran's I analysis revealed that the autocorrelation of LWD density within each segment was of a clustered nature, as opposed to dispersed. The local Moran's I identified specific location s of clustering and the nature of the clustering. Furthermore, spectral analysis of LWD density over distance indicated that, in many locations, the distances between areas of maximum LWD density were consistent and thus displayed a periodic pattern of arrangement. Segment Six displayed the strongest periodicity, with distances of 1,371 m between maximum densities occurring consistently along the entire segment. Theoretical models of LWD dynamics suggest that lower gradient river systems such as the Big River are likely to display random patterns of LWD arrangement, given the consistent source of riparian wood, the high wood transport capacity, and the inconsistent spacing of potential trapping sites; however, this research has shown that LWD distribution is not random, and displays identifiable spatial patterns. Additionally, this step of the research demonstrated a novel application of traditional time series statistical techniques, adapted for longitudinal river systems analysis.

2) Longitudinal patterns of LWD density are periodic at multiple spatial scales.

The spectral analysis not only identified significant periodic distribution of LWD, but it also identified periodicity at multiple scales, particularly in segments Two, Three, Four and Five. Within these four segments, the spectral analysis showed that the lower range of periodicity was between 200 and 1,000 m, and the higher range of periodicity was between 900 and 3,200 m. Additionally, the multi-scale periodicity in segment Four appears to be of a fractal, or self-replicating, nature. The existence of a multi-scale periodic pattern suggests that the physical mechanisms responsible for LWD arrangement, such as sinuosity, are likely to operate across multiple scales and display fractal properties.

3) **Periodicity is positively associated with meander wavelength and bar spacing, and LWD density correlated most often with valley width and sinuosity.**

Three segment-scale variables were investigated as possible controls on the periodic pattern of LWD arrangement. No significant correlation was identified; however, the variable that correlated best with periodicity was meander wavelength. The segments that contained the most consistent periodic pattern, segments Five and Six, displayed periodicities that nearly matched the meander wavelength of the segments. Segment Five had a periodicity of 1,071 m and a meander wavelength of 1,127 m, and segment Six had a periodicity of 1,371m and a meander wavelength of 1,538 m.

Fourteen other variables were investigated as possible controls of LWD density in the Big River. Statistical tests of association, correlation and regression, were performed to identify relationships between LWD density and the possible controls using three different sets of data: (1) data across all segments, (2) data within individual segments, and (3) data within specific reaches identified as having significant periodicity. In correlation analysis across all segments, three factors were weakly correlated with LWD density: drainage area, 500-m sinuosity, and left bank wooded width. However, we were unable to successfully fit a Poisson regression model of LWD density. When correlation was tested within individual segments, twice as many variables were significantly correlated with LWD density; however, significantly correlated variables varied among segments. Valley width was the most consistently correlated variable, correlating with LWD density in four of the seven segments. Poisson regression models were successfully developed (X^2 P > 0.001) for three of the seven segments. Although the regression models included a high number (5) of variables, valley width was selected as one of those variables in each model. Then, correlation analysis performed within individual reaches that displayed a significant periodic arrangement (nine reaches among six segments), showed that significant correlations were even more variable, with all but one control variable being correlated at least once among the reaches. Poisson regression models were successfully developed (X^2 P > 0.001) for five of the nine reaches. In this case, 100-m sinuosity was the variable most consistently selected by the stepwise Poisson regression.

Although relationships were not consistently strong, the persistence of valley width, and sinuosity as being associated with LWD density indicates that, of the 14 variables investigated, these two contribute most to the explanation of LWD density patterns. In general, LWD density was positively associated with sinuosity when sinuosity was measured over a distance of 100 m. LWD density was negatively associated with valley width. It is likely that valley width was consistently associated with LWD density because of its relationship to sinuosity. Due to the semi-confined morphology of the Big River, meandering is often controlled by the valley width, such that meander wavelengths become shorter, producing a higher frequency of meandering when the valley narrows, and vice versa when the valley widens (Figure 5.1). So, we conclude that at the 100-m scale (essentially the low flow channel), LWD density is in part controlled by sinuosity, but the sinuosity is controlled by confinement of the valley. The semi-confined morphology of the Big River strongly confines the channel in some locations, and at other locations allows the channel to meander freely. Therefore, our ability to model LWD density based on sinuosity will be dependent on our ability to model the dynamic meander patterns created by the semi-confined morphology of the Big River.

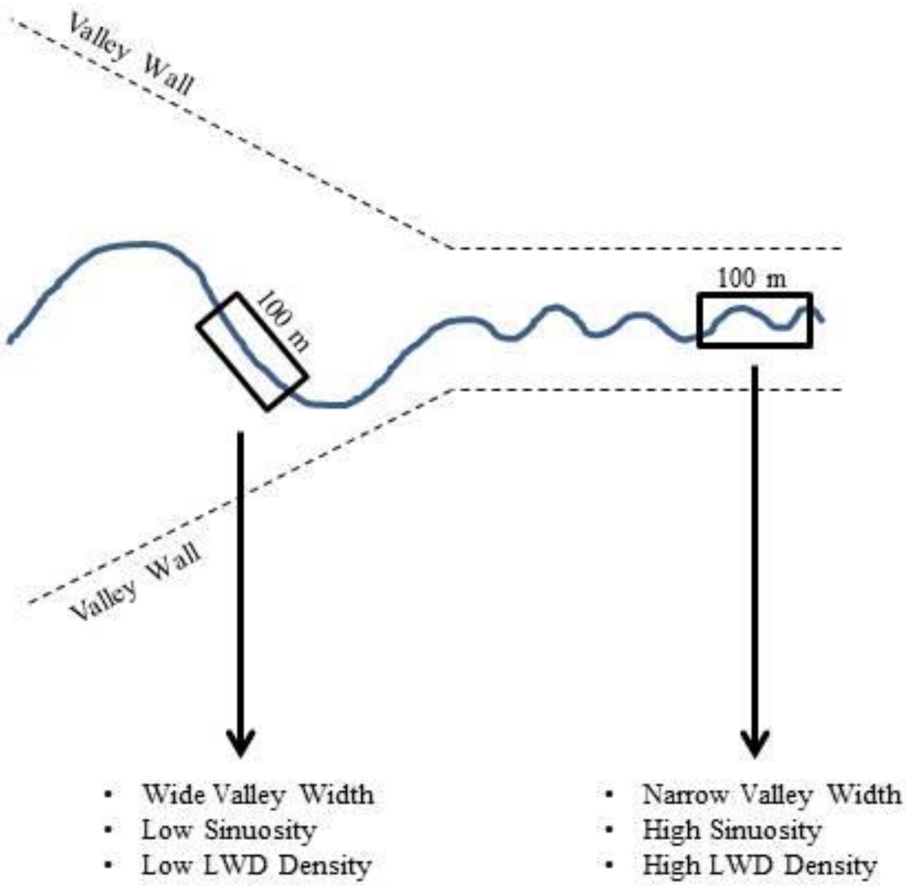


Figure 5.1. Conceptual diagram of valley controlled meander pattern in the Big River. LWD density was positively associated with sinuosity measured over a distance of 100 m, and negatively associated valley width.

4) In the Big River, fluvial wood loads are high relative to those of other low-gradient systems, transport capacity is high, and the dominant wood recruitment mechanism is bank erosion.

No baseline LWD data exist for river systems like the Big River, therefore increasingly popular management techniques that involve the placement of wood in similar river systems are based on potentially inappropriate models. I found that wood loads in the Big River are low compared to those in montane regions, such as the Pacific Northwest, and high compared to those in low-gradient coastal systems, such as the Congaree River in coastal South Carolina. Furthermore, wood size characteristics indicate that LWD pieces in the Big River tend to be larger than those of other regions. The large size of LWD pieces, along with field observations, support the interpretation that bank erosion is a dominant recruitment mechanism for this river system. Additionally, relationships between wood size and channel geometry indicate that fluvial wood transport capacity in the Big River is high relative to that of other regions.

5) Fluvial wood has little effect on reach-scale sediment storage except where large pieces are oriented perpendicular to the direction of flow.

This research demonstrated that, although LWD has been identified as a significant factor affecting sediment storage in some river systems, its effect on sediment storage in the Big River is negligible. A notable exception was found in the BFA reach, in which LWD was responsible for storing nearly 5% of all in-channel sediment. The greater storage volume in the BFA reach can be attributed to the unlikely perpendicular orientation of a single piece of LWD. Furthermore, there was no difference between piece-related sediment storage and jam-related sediment storage. Additionally, no relationships were found between LWD characteristics and sediment size characteristics. Sediment stored by LWD displayed a size distribution typical of that found in stored channel sediments of the Big River and reflected the influence of mine-waste-related sediments found downstream of the LWA reach. Although the influence of LWD on sediment storage in the Big River is negligible, the exception found in the BFA reach demonstrates the potential of LWD to affect a river's sediment budget.

5.2. Recommendations for Future Research

It will be necessary to study LWD dynamics in other mid-gradient, semi-confined, Midwestern river systems to better understand the role of LWD and the variability of fluvial wood loads in similar river systems. Midwestern river systems are probably some of the most human-impacted systems in the country, considering the prevalence of agricultural land use and other historical land use patterns. However, growing understanding of the ecological importance of the riparian zone has resulted in management practices that are increasingly aimed at protecting and restoring riparian areas of Midwestern rivers. As such, there are opportunities to enhance our understanding of the role of LWD by comparing similar types of river systems that are at various stages of riparian succession and in different stages of land-use change.

To develop a better understanding of LWD dynamics in Midwestern rivers, it will also be necessary to refine LWD metrics and the way those metrics are measured. Useful comparisons will require a unified method for assessing LWD dynamics in river systems and agreement about the most appropriate scales of measurement because, as this research has demonstrated, relationships and patterns vary over multiple scales of measurement. It will also be necessary to recognize, and subsequently develop, field methods tailored to LWD of particular systems. All LWD is not equal. For instance, the method typically used to calculate jam volume, and used in this study, is to simply take the product of the length, width, and height of the jam. Field observations indicated that this method was likely to overestimate the volume of many "jams" in the Big River due to the configuration of pieces and lack of accumulated smaller material in the interstices of the jam. For this reason, it may be more useful to re-evaluate what defines an LWD "jam." In rivers like the Big River, it would be far more accurate to incorporate a variable that represents void space within the jam into the volume calculation. The method used here to calculate jam volume is more likely to be accurate when applied to larger jams, which were relatively infrequent within the bankfull channel of the Big River and much more frequent on the river's floodplains.

This research was designed to investigate LWD within the bankfull channel because LWD-related management techniques most frequently involve addition of LWD within this zone. However, field observations indicated that a majority of LWD in the Big River is transported during out-of-bank floods and that large volumes of LWD collect on the floodplains during out-of-bank floods. Numerous large LWD jams that were seen outside of the bankfull channel and on the floodplain and may indicate that the floodplain serves as a primary trapping site for LWD in this system. In order to develop a comprehensive understanding of wood dynamics in the Big River, and similar river systems, it will be necessary to also investigate characteristics of floodplain LWD.

One of the key limitations to our understanding of LWD dynamics in river systems is time. Very few studies have investigated the interaction of LWD with river systems over time. The research presented here did not incorporate a temporal component; however, because the second field expedition took place nearly one year after the first, it was possible to conduct a repeat survey on one segment, segment Four, during the second expedition. Although LWD density increased from 2012 to 2013, and spatial patterns of wood arrangement were similar: 100-m sections that had contained high LWD densities in 2012 still had high densities, and 100-m sections that had contained low LWD densities in 2012 still contained low densities. Repeat surveys of multiple segments, encompassing a wide range of flow magnitude, over multiple years would ultimately be necessary to test the long-term stability of patterns of fluvial wood density. More temporal LWD studies are needed to better understand wood residence times, changes in transport capacity, and wood load response to watershed management practices and changing land use, and, ultimately, to understand the response of fluvial wood to changing climate conditions.

5.3. Implications for Management Practices that Involve LWD

The Big River provides an example of a river system in which the relationships between LWD and the fluvial system were poorly understood, yet it also exemplifies a type of river system in which restoration projects frequently involve the addition of LWD to the channel, for various reasons. Ultimately, managers will require accurate models of LWD arrangement to understand where LWD placement is more likely to succeed. This research did not set out to create such a model, but has provided an analysis of LWD that can serve as a baseline for comparison with other similar systems. If the findings of this research can be confirmed and strengthened through comparison, models of LWD arrangement based on common physical and riparian parameters can be created and applied to other low-gradient river systems in the Midwest.

If LWD is intended for use as a natural means of stream management or rehabilitation in the Big River, specifically, this research can help guide that effort. Based on the findings of this research, LWD has very little impact on sediment storage in the Big River. Therefore, efforts to use LWD as a sediment regulator, as has been done in other regions, will likely be ineffective without a greater engineering effort. Addition of LWD for the purpose of habitat enhancement should be sensitive to the location of LWD placement. This research found the density of LWD to be periodic in many locations, and positively correlated to channel-scale sinuosity. Therefore, wood placements should occur in locations where small-scale (low-flow channel) sinuosity is high. Additionally, the high transport capacity of the Big River should be taken into consideration. Due to the high capacity, smaller pieces of LWD would be more likely to become mobile and thus larger LWD, which this research has identified as being characteristic of the Big river, would be a better choice if wood is to be placed in the river.

APPENDICES

Appendix A. R code for spectral analysis and wavelet analysis

SPECTRAL ANALYSIS AND THE PERIODOGRAM
Example from Segment 7

```
MA.spec7 <- spec.pgram(seg7_MA$MA, taper = 0, plot = "false")

spec.df7MA <- data.frame(freq =MA.spec7$freq, spec = MA.spec7$spec)

ms.period <- rev(c(100,500, 1000, 1500, 3000, 4500))

ms.labels <- rev(c("100","500", "1000", "1500", "3000", "4500"))

spec.df7MA$period <- (1/spec.df7MA$freq)*100

plot7<-ggplot(data = subset(spec.df7MA)) + geom_line(aes(x = period, y = spec),
col="blue") + scale_x_log10("Period (m)", breaks = ms.period, labels = ms.labels) +
scale_y_continuous("Power Spectrum") + theme(text=element_text(size=8,
family="Times New Roman")) + annotate("text", x = 475, y = 35, label = "Segment 7",
family="Times New Roman", size = 3) +
theme(plot.margin=unit(x=c(0,2,0,0),units="mm"))

plot7
```

WAVELET ANALYSIS

```
library(dplR)

wave.out<-morlet(y1 = seg2_MA$MA5pt, x1 = seg2_MA$Cell)

wavelet.plot(wave.out, x.lab=gettext("River Km"), period.lab=gettext("Distance x 100m"))
```

Appendix B. R Code for Spectral Density Analysis

```
>MA.spec1 <- spec.pgram(seg1_MA$MA, taper = 0, plot = "false")

#make dataframe #
>spec.df1MA <- data.frame(freq =MA.spec1$freq, spec = MA.spec1$spec)

>ms.period <- rev(c(250, 500, 1000, 2500, 5000, 10000, 20000, 40000))

>ms.labels <- rev(c("250", "500", "1000", "2500", "5000", "10000", "20000",
"40000"))

>spec.df1MA$period <- (1/spec.df1MA$freq)*100

>plot1<-ggplot(data = subset(spec.df1MA)) + geom_line(aes(x = period, y =
spec), col="black") + scale_x_log10("Distance (m)",breaks = ms.period, labels
= ms.labels) + scale_y_continuous("Power Spectrum") +
theme(text=element_text(size=12, family="Times New Roman"))+ annotate("text",
x = 500, y = 75, label = "Segment 1", family="Times New Roman", size = 3)+
theme(plot.margin=unit(x=c(2,0,0,0),units="mm"))

>plot1
```

Appendix C. R Code and output for Regressions

LINNEAR STEPWISE REGRESSION OF PERIODICITY

```
> summary(pmod)

Call:
lm(formula = per ~ bspace, data = period_lm)

Residuals:
      1       2       3       4       5       6       7 
 -34.34  691.16  -95.60 -748.07  175.99   98.97  -88.10 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -668.269    861.121  -0.776    0.473
bspace         2.299      1.278   1.799    0.132

Residual standard error: 468.2 on 5 degrees of freedom
Multiple R-squared:  0.3929,	Adjusted R-squared:  0.2715 
F-statistic: 3.236 on 1 and 5 DF,  p-value: 0.1319
```

STEP-WISE POISSON REGRESSION FOR ALL SEGMENTS COMBINED

```
> glm_h2<-glm(Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin +
X500m.Sin + X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
Elev. + Slope + Bar.Space, family=poisson(), data=h2_corr)
>
> step(glm_h2)
Start:  AIC=4877.36
Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin +
    X500m.Sin + X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth +
    Tot..Wdth + Elev. + Slope + Bar.Space

              Df Deviance    AIC
- Trib..Dist.  1   1808.1 4875.4
- Bar.Area     1   1809.0 4876.3
<none>             1808.0 4877.4
- Chan..W.     1   1811.1 4878.4
- X100m.Sin    1   1811.6 4878.9
- X1000m.Sin   1   1811.9 4879.2
- Conf.        1   1815.0 4882.3
- RB.Wdth      1   1815.4 4882.7
- Tot..Wdth    1   1815.5 4882.8
- LB.Wdth      1   1815.5 4882.8
- Slope        1   1819.2 4886.6
- Vall..W.     1   1820.7 4888.0
- Elev.        1   1820.8 4888.1
- X500m.Sin    1   1821.4 4888.7
- Ad           1   1834.7 4902.0
- Bar.Space    1   1894.8 4962.1

Step:  AIC=4875.43
Dens ~ Chan..W. + Vall..W. + Conf. + X100m.Sin + X500m.Sin +
    X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
    Elev. + Slope + Bar.Space

             Df Deviance    AIC
- Bar.Area    1   1809.0 4874.3
<none>            1808.1 4875.4
- Chan..W.    1   1811.2 4876.5
- X100m.Sin   1   1811.7 4877.0
- X1000m.Sin  1   1811.9 4877.2
- Conf.       1   1815.0 4880.3
- RB.Wdth     1   1815.4 4880.7
- Tot..Wdth   1   1815.5 4880.8
- LB.Wdth     1   1815.5 4880.8
- Slope       1   1819.4 4884.7
- Vall..W.    1   1820.7 4886.0
- Elev.       1   1820.8 4886.1
- X500m.Sin   1   1821.9 4887.2
- Ad          1   1834.7 4900.0
- Bar.Space   1   1902.4 4967.7

Step:  AIC=4874.31
Dens ~ Chan..W. + Vall..W. + Conf. + X100m.Sin + X500m.Sin +
    X1000m.Sin + Ad + RB.Wdth + LB.Wdth + Tot..Wdth + Elev. +
    Slope + Bar.Space
```

```
               Df Deviance    AIC
<none>               1809.0 4874.3
- Chan..W.      1   1811.4 4874.7
- X100m.Sin     1   1812.6 4875.9
- X1000m.Sin    1   1812.9 4876.2
- Conf.         1   1815.9 4879.2
- RB.Wdth       1   1816.2 4879.5
- Tot..Wdth     1   1816.2 4879.5
- LB.Wdth       1   1816.2 4879.6
- Slope         1   1820.2 4883.5
- Vall..W.      1   1821.5 4884.8
- Elev.         1   1822.0 4885.3
- X500m.Sin     1   1822.8 4886.1
- Ad            1   1835.8 4899.1
- Bar.Space     1   1903.9 4967.2

Call:  glm(formula = Dens ~ Chan..W. + Vall..W. + Conf. + X100m.Sin +
    X500m.Sin + X1000m.Sin + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
    Elev. + Slope + Bar.Space, family = poisson(), data = h2_corr)

Coefficients:
(Intercept)     Chan..W.     Vall..W.        Conf.    X100m.Sin
  2.1118958   -0.0015285    0.0003951   -0.0106234   -1.0752313
  X500m.Sin   X1000m.Sin           Ad      RB.Wdth      LB.Wdth
 -0.7386097   -0.1452372    0.0005760   -2.1608131   -2.1638175
  Tot..Wdth        Elev.        Slope    Bar.Space
  2.1626982    0.0083041   -0.4099479   -0.0012624

Degrees of Freedom: 979 Total (i.e. Null);  966 Residual
Null Deviance:      2009
Residual Deviance: 1809        AIC: 4874
```

```
Call:  glm(formula = Dens ~ Chan..W. + Vall..W. + Conf. + X100m.Sin +
    X500m.Sin + X1000m.Sin + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
    Elev. + Slope + Bar.Space, family = poisson(), data = h2_corr)

Coefficients:
(Intercept)     Chan..W.     Vall..W.        Conf.    X100m.Sin    X500m.Sin
  2.1118958   -0.0015285    0.0003951   -0.0106234   -1.0752313   -0.7386097
 X1000m.Sin           Ad      RB.Wdth      LB.Wdth    Tot..Wdth        Elev.
 -0.1452372    0.0005760   -2.1608131   -2.1638175    2.1626982    0.0083041
      Slope    Bar.Space
 -0.4099479   -0.0012624

Degrees of Freedom: 979 Total (i.e. Null);  966 Residual
Null Deviance:      2009
Residual Deviance: 1809        AIC: 4874
> h2_step<-glm(Dens ~ Chan..W. + Vall..W. + Conf. + X100m.Sin + X500m.Sin +
X1000m.Sin + Ad + RB.Wdth + LB.Wdth + Tot..Wdth + Elev. + Slope + Bar.Space,
family=poisson(), data=h2_corr)
> with(h2_step, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance  df            p
[1,]     1809.006 966 7.227041e-54
```

STEPWISE POISSON REGRESSION FOR INDIVIDUAL SEGMENTS

ENTIRE STEPWISE SEQUENCE ONLY SHOWN FOR SEGMENT 1.

##SEGMENT 1##

```
> glm_seg1<-glm(Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin
+ X500m.Sin + X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
Elev. + Slope + Bar.Space, family=poisson(), data=seg1_corr)
>
> step(glm_seg1)
Start:  AIC=569.74
Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin +
    X500m.Sin + X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth +
    Tot..Wdth + Elev. + Slope + Bar.Space


Step:  AIC=569.74
Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin +
    X500m.Sin + X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth +
    Tot..Wdth + Elev. + Slope

              Df Deviance    AIC
- X500m.Sin    1   189.61 567.84
- Vall..W.     1   189.70 567.93
- Ad           1   189.95 568.18
- Slope        1   190.15 568.38
- Conf.        1   190.46 568.70
- Trib..Dist.  1   191.29 569.53
- LB.Wdth      1   191.33 569.57
- RB.Wdth      1   191.33 569.57
- Tot..Wdth    1   191.33 569.57
<none>             189.51 569.74
- X100m.Sin    1   192.10 570.33
- X1000m.Sin   1   193.75 571.98
- Chan..W.     1   194.19 572.43
- Bar.Area     1   204.15 582.38
- Elev.        1   205.99 584.22

Step:  AIC=567.84
Dens ~ Chan..W. + Vall..W. + Conf. + Trib..Dist. + X100m.Sin +
    X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth +
    Elev. + Slope

              Df Deviance    AIC
- Vall..W.     1   189.74 565.97
- Ad           1   190.06 566.29
- Slope        1   190.19 566.42
- Conf.        1   190.51 566.75
- Trib..Dist.  1   191.32 567.56
- LB.Wdth      1   191.49 567.73
- RB.Wdth      1   191.50 567.73
- Tot..Wdth    1   191.50 567.73
<none>             189.61 567.84
- X100m.Sin    1   192.13 568.37
- Chan..W.     1   194.24 570.47
- X1000m.Sin   1   194.77 571.00
- Bar.Area     1   204.15 580.38
- Elev.        1   206.00 582.23
```

```
Step:  AIC=565.97
Dens ~ Chan..W. + Conf. + Trib..Dist. + X100m.Sin + X1000m.Sin + 
    Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth + Elev. + Slope

              Df Deviance    AIC
- Ad           1   190.08 564.32
- Slope        1   190.22 564.46
- Conf.        1   190.55 564.78
- Trib..Dist.  1   191.34 565.58
- LB.Wdth      1   191.56 565.80
- RB.Wdth      1   191.57 565.80
- Tot..Wdth    1   191.57 565.80
<none>             189.74 565.97
- X100m.Sin    1   192.34 566.57
- Chan..W.     1   194.41 568.64
- X1000m.Sin   1   194.77 569.01
- Bar.Area     1   205.94 580.17
- Elev.        1   206.00 580.23

Step:  AIC=564.32
Dens ~ Chan..W. + Conf. + Trib..Dist. + X100m.Sin + X1000m.Sin + 
    Bar.Area + RB.Wdth + LB.Wdth + Tot..Wdth + Elev. + Slope

              Df Deviance    AIC
- Slope        1   190.55 562.78
- Conf.        1   191.17 563.40
- LB.Wdth      1   191.88 564.11
- RB.Wdth      1   191.88 564.11
- Tot..Wdth    1   191.88 564.11
<none>             190.08 564.32
- Trib..Dist.  1   192.21 564.44
- X100m.Sin    1   192.75 564.98
- Chan..W.     1   194.50 566.74
- X1000m.Sin   1   194.79 567.02
- Bar.Area     1   205.94 578.17
- Elev.        1   218.26 590.50

Step:  AIC=562.78
Dens ~ Chan..W. + Conf. + Trib..Dist. + X100m.Sin + X1000m.Sin + 
    Bar.Area + RB.Wdth + LB.Wdth + Tot..Wdth + Elev.

              Df Deviance    AIC
- LB.Wdth      1   192.35 562.58
- RB.Wdth      1   192.35 562.58
- Tot..Wdth    1   192.35 562.58
- Conf.        1   192.35 562.59
<none>             190.55 562.78
- X100m.Sin    1   193.62 563.85
- Trib..Dist.  1   194.31 564.54
- X1000m.Sin   1   195.30 565.53
- Chan..W.     1   195.40 565.63
- Bar.Area     1   205.95 576.18
- Elev.        1   232.74 602.97

Step:  AIC=562.58
Dens ~ Chan..W. + Conf. + Trib..Dist. + X100m.Sin + X1000m.Sin + 
    Bar.Area + RB.Wdth + Tot..Wdth + Elev.
```

```
               Df Deviance    AIC
- RB.Wdth       1   192.59 560.82
- Tot..Wdth     1   193.79 562.03
- Conf.         1   194.06 562.29
<none>              192.35 562.58
- X100m.Sin     1   195.42 563.65
- Trib..Dist.   1   196.01 564.24
- X1000m.Sin    1   196.99 565.22
- Chan..W.      1   197.11 565.34
- Bar.Area      1   207.81 576.04
- Elev.         1   235.47 603.70

Step:  AIC=560.82
Dens ~ Chan..W. + Conf. + Trib..Dist. + X100m.Sin + X1000m.Sin +
    Bar.Area + Tot..Wdth + Elev.

               Df Deviance    AIC
- Conf.         1   194.31 560.55
- Tot..Wdth     1   194.36 560.59
<none>              192.59 560.82
- X100m.Sin     1   195.58 561.81
- Trib..Dist.   1   196.12 562.35
- X1000m.Sin    1   197.27 563.51
- Chan..W.      1   197.62 563.85
- Bar.Area      1   209.06 575.29
- Elev.         1   235.60 601.83

Step:  AIC=560.55
Dens ~ Chan..W. + Trib..Dist. + X100m.Sin + X1000m.Sin + Bar.Area +
    Tot..Wdth + Elev.

               Df Deviance    AIC
<none>              194.31 560.55
- X100m.Sin     1   197.16 561.39
- Trib..Dist.   1   197.48 561.71
- Tot..Wdth     1   197.50 561.74
- Chan..W.      1   197.66 561.89
- X1000m.Sin    1   199.04 563.27
- Bar.Area      1   211.36 575.59
- Elev.         1   236.17 600.40

Call:  glm(formula = Dens ~ Chan..W. + Trib..Dist. + X100m.Sin + X1000m.Sin +
    Bar.Area + Tot..Wdth + Elev., family = poisson(), data = seg1_corr)

Coefficients:
(Intercept)     Chan..W.  Trib..Dist.    X100m.Sin   X1000m.Sin
 -1.139e+01   -5.450e-03    2.840e-02   -2.427e+00   -5.904e-01
   Bar.Area    Tot..Wdth        Elev.
  1.557e-04    3.966e-03    6.618e-02

Degrees of Freedom: 105 Total (i.e. Null);  98 Residual
Null Deviance:      355.8
Residual Deviance: 194.3        AIC: 560.5
```

##NOW, RERUN GLM WITH VARIABLES SELECTED BY STEP()##

```
> glm_seg1<-glm(Dens ~ Chan..W. + Trib..Dist. + X100m.Sin + X1000m.Sin +
Bar.Area + Elev. + Tot..Wdth, family=poisson(), data=seg1_corr)
> summary(glm_seg1)

Call:
glm(formula = Dens ~ Chan..W. + Trib..Dist. + X100m.Sin + X1000m.Sin +
    Bar.Area + Elev. + Tot..Wdth, family = poisson(), data = seg1_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.6606  -0.9877  -0.2245   0.7587   4.5195

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -1.139e+01  2.842e+00  -4.007 6.16e-05 ***
Chan..W.    -5.450e-03  3.007e-03  -1.813   0.0699 .
Trib..Dist.  2.840e-02  1.570e-02   1.809   0.0704 .
X100m.Sin   -2.427e+00  1.471e+00  -1.650   0.0989 .
X1000m.Sin  -5.904e-01  2.814e-01  -2.098   0.0359 *
Bar.Area     1.557e-04  3.731e-05   4.172 3.02e-05 ***
Elev.        6.618e-02  9.691e-03   6.829 8.56e-12 ***
Tot..Wdth    3.966e-03  2.269e-03   1.748   0.0804 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 355.80  on 105  degrees of freedom
Residual deviance: 194.31  on  98  degrees of freedom
AIC: 560.55

Number of Fisher Scoring iterations: 5

> with(glm_seg1, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df            p
[1,]     194.3144 98 2.50027e-08
```

##SEGMENT 2##

```
> glm_seg2<-glm(Dens ~ Chan..W. + Vall..W. + X1000m.Sin + Bar.Area + LB.Wdth, 
family=poisson(), data=seg2_corr)
> summary(glm_seg2)

Call:
glm(formula = Dens ~ Chan..W. + Vall..W. + X1000m.Sin + Bar.Area + 
    LB.Wdth, family = poisson(), data = seg2_corr)

Deviance Residuals: 
     Min        1Q    Median        3Q       Max  
-2.91480  -0.75296  -0.09007   0.60824   2.86713  

Coefficients:
              Estimate Std. Error z value Pr(>|z|)    
(Intercept)  2.372e+00  2.458e-01   9.652  < 2e-16 ***
Chan..W.    -3.812e-03  2.587e-03  -1.474 0.140563    
Vall..W.    -5.563e-04  1.619e-04  -3.437 0.000589 ***
X1000m.Sin  -4.314e-01  1.746e-01  -2.471 0.013471 *  
Bar.Area     6.609e-05  3.731e-05   1.771 0.076480 .  
LB.Wdth     -5.386e-03  2.425e-03  -2.221 0.026363 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 295.84  on 219  degrees of freedom
Residual deviance: 259.81  on 214  degrees of freedom
AIC: 891.6

Number of Fisher Scoring iterations: 5

> with(glm_seg2, cbind(res.deviance = deviance, df = df.residual, p = 
pchisq(deviance, 
+ 
df.residual, lower.tail = FALSE)))
     res.deviance  df          p
[1,]     259.8066 214 0.01764326
```

##SEGMENT 3##

```
> glm_seg3<-glm(Dens ~ X500m.Sin + Bar.Area + Tot..Wdth, family=poisson(),
data=seg3_corr)
> summary(glm_seg3)

Call:
glm(formula = Dens ~ X500m.Sin + Bar.Area + Tot..Wdth, family = poisson(),
    data = seg3_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.0289  -1.0743  -0.1150   0.6233   3.8684

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.824e+00  4.452e-01   4.097 4.18e-05 ***
X500m.Sin   -6.502e-01  3.890e-01  -1.671   0.0946 .
Bar.Area     5.225e-05  2.929e-05   1.784   0.0744 .
Tot..Wdth    3.561e-03  1.570e-03   2.268   0.0233 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 379.34  on 220  degrees of freedom
Residual deviance: 367.61  on 217  degrees of freedom
AIC: 1057.8

Number of Fisher Scoring iterations: 5

> with(glm_seg3, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance  df            p
[1,]      367.606 217 7.289476e-10
```

##SEGMENT 4##

```
> glm_seg4<-glm(Dens ~ Vall..W. + Ad + RB.Wdth + Trib..Dist. + Tot..Wdth,
family=poisson(), data=seg4_corr)
> summary(glm_seg4)

Call:
glm(formula = Dens ~ Vall..W. + Ad + RB.Wdth + Trib..Dist. +
    Tot..Wdth, family = poisson(), data = seg4_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.1641  -0.8667  -0.1369   0.5075   4.3062

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  3.5382415  0.5494701   6.439 1.20e-10 ***
Vall..W.    -0.0002542  0.0001361  -1.867 0.061874 .
Ad          -0.0008452  0.0002422  -3.490 0.000484 ***
RB.Wdth      0.0063507  0.0029032   2.187 0.028707 *
Trib..Dist. -0.0440798  0.0110937  -3.973 7.09e-05 ***
Tot..Wdth   -0.0054943  0.0021011  -2.615 0.008925 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 296.75  on 202  degrees of freedom
Residual deviance: 272.35  on 197  degrees of freedom
AIC: 905.37

Number of Fisher Scoring iterations: 5

> with(glm_seg4, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance  df            p
[1,]     272.3467 197 0.0003014996
```

##SEGMENT 5##

```
> glm_seg5<-glm(Dens ~ Vall..W. + Trib..Dist. + Bar.Area +Conf. +X500m.Sin,
family=poisson(), data=seg5_corr)
> summary(glm_seg5)

Call:
glm(formula = Dens ~ Vall..W. + Trib..Dist. + Bar.Area + Conf. +
    X500m.Sin, family = poisson(), data = seg5_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.2942  -0.7337  -0.1666   0.6321   2.1587

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  8.364e+00  2.228e+00   3.755 0.000174 ***
Vall..W.    -3.490e-03  1.243e-03  -2.809 0.004974 **
Trib..Dist. -4.847e-02  3.350e-02  -1.447 0.147931
Bar.Area     4.988e-05  3.179e-05   1.569 0.116625
Conf.        9.464e-02  4.837e-02   1.957 0.050385 .
X500m.Sin   -5.004e+00  1.838e+00  -2.723 0.006468 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 107.854  on 73  degrees of freedom
Residual deviance:  76.136  on 68  degrees of freedom
AIC: 342.1

Number of Fisher Scoring iterations: 4

> with(glm_seg5, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df         p
[1,]       76.136 68 0.2332199
```

##SEGMENT 6##

```
> glm_seg6<-glm(Dens ~ Trib..Dist. + X100m.Sin + Ad + X500m.Sin + Slope +
LB.Wdth, family=poisson(), data=seg6_corr)
> summary(glm_seg6)

Call:
glm(formula = Dens ~ Trib..Dist. + X100m.Sin + Ad + X500m.Sin +
    Slope + LB.Wdth, family = poisson(), data = seg6_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.3110  -0.9683  -0.1903   0.6348   3.2477

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -15.959800  13.423856  -1.189  0.23447
Trib..Dist.   0.020208   0.009689   2.086  0.03701 *
X100m.Sin    -5.045536   2.371185  -2.128  0.03335 *
Ad            0.011332   0.005829   1.944  0.05189 .
X500m.Sin    -1.776171   0.630748  -2.816  0.00486 **
Slope         6.572368   2.679743   2.453  0.01418 *
LB.Wdth      -0.013565   0.003321  -4.084 4.43e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 222.06  on 93  degrees of freedom
Residual deviance: 175.03  on 87  degrees of freedom
AIC: 495.41

Number of Fisher Scoring iterations: 5

> with(glm_seg6, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df            p
[1,]     175.0339 87 7.047069e-08
```

##SEGMENT 7##

```
> glm_seg7<-glm(Dens ~ Chan..W. + Conf. + Trib..Dist. + X500m.Sin +
X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth, family=poisson(),
data=seg7_corr)
> summary(glm_seg7)

Call:
glm(formula = Dens ~ Chan..W. + Conf. + Trib..Dist. + X500m.Sin +
    X1000m.Sin + Bar.Area + Ad + RB.Wdth + LB.Wdth + Tot..Wdth,
    family = poisson(), data = seg7_corr)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.4138  -1.0766  -0.1403   0.7070   2.2631

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  6.364e+02  1.414e+02   4.502 6.73e-06 ***
Chan..W.    -1.838e-02  5.024e-03  -3.659 0.000253 ***
Conf.       -3.999e-02  1.168e-02  -3.424 0.000617 ***
Trib..Dist.  6.155e-01  1.512e-01   4.071 4.69e-05 ***
X500m.Sin   -1.114e+00  5.019e-01  -2.219 0.026474 *
X1000m.Sin   7.379e-01  1.673e-01   4.410 1.04e-05 ***
Bar.Area     1.124e-04  5.323e-05   2.113 0.034631 *
Ad          -2.552e-01  5.700e-02  -4.477 7.56e-06 ***
RB.Wdth     -2.425e+00  1.328e+00  -1.826 0.067792 .
LB.Wdth     -2.417e+00  1.328e+00  -1.819 0.068849 .
Tot..Wdth    2.422e+00  1.328e+00   1.823 0.068274 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 148.80  on 60  degrees of freedom
Residual deviance: 103.35  on 50  degrees of freedom
AIC: 329.1

Number of Fisher Scoring iterations: 5

> with(glm_seg7, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df            p
[1,]     103.3468 50 1.391448e-05
```

<u>REACH-SPECIFIC STEPWISE POISSON REGRESSIONS</u>

STEPWISE OUTPUTS NOT SHOWN HERE FOR THE SAKE OF SAVING SPACE.

The results shown below are the glm's created from the step-wise variable selection.

<u>##SEGMENT 2A##</u>

```
> glm_seg2a<-glm(Dens ~ Chan..W. + Conf. + X100m.Sin + Bar.Area + LB.Wdth,
family=poisson(), data=seg2_suba)
> summary(glm_seg2a)

Call:
glm(formula = Dens ~ Chan..W. + Conf. + X100m.Sin + Bar.Area +
    LB.Wdth, family = poisson(), data = seg2_suba)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.6837  -0.8720  -0.1338   0.6520   2.2183

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  5.121e+00  2.106e+00   2.432   0.0150 *
Chan..W.    -5.458e-03  3.755e-03  -1.453   0.1461
Conf.       -1.357e-02  9.209e-03  -1.474   0.1405
X100m.Sin   -3.207e+00  2.088e+00  -1.536   0.1245
Bar.Area     8.406e-05  4.777e-05   1.760   0.0784 .
LB.Wdth     -6.504e-03  3.020e-03  -2.154   0.0313 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 141.55  on 111  degrees of freedom
Residual deviance: 128.58  on 106  degrees of freedom
AIC: 468.64

Number of Fisher Scoring iterations: 5

> with(glm_seg2a, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance  df          p
[1,]       128.58 106 0.06710988
```

##SEGMENT 2B##

```
> glm_seg2b<-glm(Dens ~ Vall..W. + Conf. + X1000m.Sin + Ad + RB.Wdth + Elev.,
family=poisson(), data=seg2_subB)
> summary(glm_seg2b)

Call:
glm(formula = Dens ~ Vall..W. + Conf. + X1000m.Sin + Ad + RB.Wdth +
    Elev., family = poisson(), data = seg2_subB)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.1677  -0.6241   0.1673   0.8192   1.1451

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) 181.972546  82.009754   2.219   0.0265 *
Vall..W.      0.003065   0.001318   2.325   0.0201 *
Conf.        -0.123612   0.031179  -3.965 7.35e-05 ***
X1000m.Sin    7.031337   3.228518   2.178   0.0294 *
Ad           -0.074740   0.035779  -2.089   0.0367 *
RB.Wdth       0.018378   0.007472   2.460   0.0139 *
Elev.        -0.666100   0.285714  -2.331   0.0197 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 50.468  on 30  degrees of freedom
Residual deviance: 31.178  on 24  degrees of freedom
AIC: 135.12

Number of Fisher Scoring iterations: 5

> with(glm_seg2b, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df         p
[1,]     31.17813 24 0.1487128
```

##SEGMENT 3A##

```
> glm_seg3a<-glm(Dens ~ Conf. + Trib..Dist. + X500m.Sin + Bar.Area + Ad +
LB.Wdth + Elev., family=poisson(), data=seg3_subA)
> summary(glm_seg3a)

Call:
glm(formula = Dens ~ Conf. + Trib..Dist. + X500m.Sin + Bar.Area +
    Ad + LB.Wdth + Elev., family = poisson(), data = seg3_subA)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.9967  -1.0135  -0.1062   0.5246   4.2403

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  0.7394386  4.5751978   0.162 0.871606
Conf.        0.0466044  0.0188002   2.479 0.013178 *
Trib..Dist. -0.0229619  0.0147355  -1.558 0.119170
X500m.Sin   -1.7850800  0.8278646  -2.156 0.031064 *
Bar.Area     0.0001534  0.0000432   3.551 0.000383 ***
Ad          -0.0061115  0.0025724  -2.376 0.017509 *
LB.Wdth      0.0066564  0.0036748   1.811 0.070082 .
Elev.        0.0305049  0.0183624   1.661 0.096660 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 247.21  on 121  degrees of freedom
Residual deviance: 210.30  on 114  degrees of freedom
AIC: 608.24

Number of Fisher Scoring iterations: 5

> with(glm_seg3A, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance  df            p
[1,]     205.8308 108 4.372144e-08
```

##SEGMENT 3B##

Insufficient Data

##SEGMENT 4A##

```
> summary(glm_seg4A)

Call:
glm(formula = Dens ~ Chan..W. + X1000m.Sin + Ad + RB.Wdth + LB.Wdth,
    family = poisson(), data = seg4_subA)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.1224  -0.5990  -0.0986   0.4355   3.8378

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -1.0803059  0.8731539  -1.237   0.2160
Chan..W.     0.0042901  0.0019918   2.154   0.0313 *
X1000m.Sin   0.8124397  0.3495588   2.324   0.0201 *
Ad           0.0007206  0.0003182   2.265   0.0235 *
RB.Wdth      0.0071668  0.0037247   1.924   0.0543 .
LB.Wdth     -0.0055328  0.0033025  -1.675   0.0939 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 117.783  on 80  degrees of freedom
Residual deviance:  97.951  on 75  degrees of freedom
AIC: 363.21

Number of Fisher Scoring iterations: 5

> with(glm_seg4A, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df          p
[1,]     97.95134 75 0.03884637
```

##SEGMENT 4B##

```
> glm_seg4B<-glm(Dens ~ X100m.Sin + X500m.Sin + Bar.Area + RB.Wdth,
family=poisson(), data=seg4_subB)
> summary(glm_seg4B)

Call:
glm(formula = Dens ~ X100m.Sin + X500m.Sin + Bar.Area + RB.Wdth,
    family = poisson(), data = seg4_subB)

Deviance Residuals:
     Min         1Q    Median        3Q       Max
-1.52758  -0.46529   0.08925   0.41685   0.96862

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -2.705e+01  1.127e+01  -2.400   0.0164 *
X100m.Sin    2.402e+01  1.103e+01   2.177   0.0295 *
X500m.Sin    4.321e+00  2.297e+00   1.881   0.0599 .
Bar.Area    -3.211e-04  1.427e-04  -2.250   0.0244 *
RB.Wdth     -1.287e-02  7.439e-03  -1.730   0.0836 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 30.8798  on 20  degrees of freedom
Residual deviance:  8.7368  on 16  degrees of freedom
AIC: 81.801

Number of Fisher Scoring iterations: 4

> with(glm_seg4B, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df         p
[1,]      8.73678 16 0.9238561
```

##SEGMENT 4C##

```
> glm_seg4C<-glm(Dens ~ LB.Wdth + Tot..Wdth, family=poisson(),
data=seg4_subC)
> summary(glm_seg4C)

Call:
glm(formula = Dens ~ LB.Wdth + Tot..Wdth, family = poisson(),
    data = seg4_subC)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-3.4955  -0.9191  -0.2510   0.5892   3.3207

Coefficients:
             Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.207200   0.221614   5.447 5.11e-08 ***
LB.Wdth     -0.012999   0.005197  -2.501  0.01237 *
Tot..Wdth    0.012526   0.004392   2.852  0.00435 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 77.094  on 45  degrees of freedom
Residual deviance: 68.247  on 43  degrees of freedom
AIC: 227.96

Number of Fisher Scoring iterations: 5

> with(glm_seg4C, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df          p
[1,]     68.24676 43 0.00844092
```

##SEGMENT 5A##

```
> glm_seg5A<-glm(Dens ~ Trib..Dist. + X100m.Sin + X1000m.Sin + Slope,
family=poisson(), data=seg5_subA)
> summary(glm_seg5A)

Call:
glm(formula = Dens ~ Trib..Dist. + X100m.Sin + X1000m.Sin + Slope,
    family = poisson(), data = seg5_subA)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.22450  -0.60176   0.02152   0.30758   1.31701

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  25.1768    13.7032   1.837 0.066166 .
Trib..Dist.  -1.2247     0.3581  -3.420 0.000627 ***
X100m.Sin    25.3914     7.5650   3.356 0.000790 ***
X1000m.Sin  -21.1202     8.1028  -2.607 0.009146 **
Slope        37.5731    19.1784   1.959 0.050097 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 33.278  on 20  degrees of freedom
Residual deviance: 10.195  on 16  degrees of freedom
AIC: 91.452

Number of Fisher Scoring iterations: 4

> with(glm_seg5A, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df         p
[1,]      10.1952 16 0.8562377
```

##SEGMENT 5B##

```
> glm_seg5B<-glm(Dens ~ Trib..Dist. + X1000m.Sin + Bar.Area + LB.Wdth + Elev.
+ Slope, family=poisson(), data=seg5_subB)
> summary(glm_seg5B)

Call:
glm(formula = Dens ~ Trib..Dist. + X1000m.Sin + Bar.Area + LB.Wdth +
    Elev. + Slope, family = poisson(), data = seg5_subB)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.0246  -0.5329  -0.0333   0.3896   0.8341

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.795e+03  5.508e+02   3.259 0.001120 **
Trib..Dist. -4.407e+00  1.267e+00  -3.480 0.000502 ***
X1000m.Sin  -1.229e+01  2.724e+00  -4.512 6.42e-06 ***
Bar.Area    -2.290e-04  6.672e-05  -3.432 0.000599 ***
LB.Wdth     -1.869e-02  8.790e-03  -2.127 0.033448 *
Elev.       -1.087e+01  3.369e+00  -3.225 0.001258 **
Slope       -7.446e+02  2.730e+02  -2.727 0.006386 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 35.9607  on 18  degrees of freedom
Residual deviance:  5.1996  on 12  degrees of freedom
AIC: 86.974

Number of Fisher Scoring iterations: 4

> with(glm_seg5B, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df         p
[1,]     5.199551 12 0.9509794
```

##SEGMENT 6A##

```
> glm_seg6A<-glm(Dens ~ X1000m.Sin + LB.Wdth, family=poisson(), data=seg6_subA)
> summary(glm_seg6A)

Call:
glm(formula = Dens ~ X1000m.Sin + LB.Wdth, family = poisson(), 
    data = seg6_subA)

Deviance Residuals: 
    Min       1Q   Median       3Q      Max  
-3.2872  -1.1009  -0.1039   0.6146   2.7367  

Coefficients:
             Estimate Std. Error z value Pr(>|z|)    
(Intercept)  2.889710   0.292007   9.896  < 2e-16 ***
X1000m.Sin  -0.477012   0.192103  -2.483    0.013 *  
LB.Wdth     -0.014229   0.003363  -4.231 2.33e-05 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 137.56  on 70  degrees of freedom
Residual deviance: 116.82  on 68  degrees of freedom
AIC: 365.78

Number of Fisher Scoring iterations: 5

> with(glm_seg6A, cbind(res.deviance = deviance, df = df.residual, p = pchisq(deviance, 
+ 
df.residual, lower.tail = FALSE)))
     res.deviance df            p
[1,]     116.8243 68 0.0002140605
```

##SEGMENT 7A##

```
> glm_seg7A<-glm(Dens ~ Vall..W. + X100m.Sin + X1000m.Sin + Ad + RB.Wdth +
LB.Wdth + Elev. + Slope, family=poisson(), data=seg7_subA)
> summary(glm_seg7A)

Call:
glm(formula = Dens ~ Vall..W. + X100m.Sin + X1000m.Sin + Ad +
    RB.Wdth + LB.Wdth + Elev. + Slope, family = poisson(), data = seg7_subA)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.6045  -1.0918  -0.4505   0.8872   2.0645

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept) -1.958e+03  8.068e+02  -2.427  0.01524 *
Vall..W.     8.676e-03  3.906e-03   2.221  0.02633 *
X100m.Sin   -7.021e+00  4.289e+00  -1.637  0.10165
X1000m.Sin   1.759e+00  5.423e-01   3.244  0.00118 **
Ad           6.746e-01  2.873e-01   2.348  0.01887 *
RB.Wdth     -2.360e-02  1.272e-02  -1.855  0.06356 .
LB.Wdth     -2.158e-02  1.021e-02  -2.114  0.03450 *
Elev.        2.145e+00  8.265e-01   2.596  0.00943 **
Slope        1.112e+02  4.358e+01   2.551  0.01073 *
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 64.354  on 18  degrees of freedom
Residual deviance: 28.051  on 10  degrees of freedom
AIC: 103.49

Number of Fisher Scoring iterations: 5

> with(glm_seg7A, cbind(res.deviance = deviance, df = df.residual, p =
pchisq(deviance,
+
df.residual, lower.tail = FALSE)))
     res.deviance df           p
[1,]     28.05122 10 0.001771471
```

Appendix D. Field worksheet for reach-Scale LWD Measurements

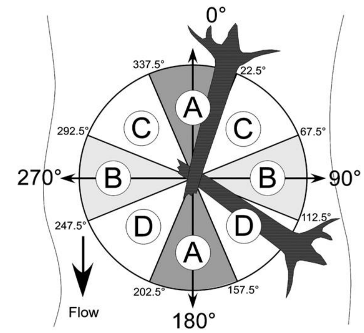
LWD/Sediment Worksheet

Recorder Initials ____________________________

Date: ____________________________

Site Name/ID: ____________________________ Orientation

Guide:



Bankfull Channel Orientation

Weather Conditions: ____________________________

Other Notes: ____

LWD							**Sediment Deposit**							
ID	Jam			Piece		Ori.	L	W	Depth (cm)			Sample ID		
	W(m)	L(m)	D(m)	L(m)	W(cm)				D1	D2	D3	S1	S2	S3

Appendix E. Reach Scale Field Measurements

Bootleg Access (BA)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**m**	**Vol (m3)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
RP1				3.54	0.11	11	0.03	24	A								
RP2				3.97	0.22	22	0.15	28	A	3.4	1.06	0.67	1.82	>2.2	BA-LP1	BA-LP1	BA-LP1
RP3				5.45	0.15	15	0.10	49	A								
LJ1	2.46	2.2	0.48			0	2.60	10									
LP1				4.26	0.25	25	0.21	16	A	1.9	0.73	0.81	0.76	0.5	BA-RP2	BA-RP2	BA-RP2
LP2				6.65	0.17	17	0.15	34	A								
LP3				4.3	0.1	10	0.03	39	A								
LP4				3.43	0.33	33	0.29	40	A								
RP4				6	0.1	10	0.05	60	A								
RP5				4.23	0.1	10	0.03	75	A								
RP6				1.02	0.2	20	0.03	80	B								
RP7				5.77	0.11	11	0.05	88	D								
LJ2	3.36	2.5	0.95			0	7.98	88									
RP8				2.45	0.19	19	0.07	89	A								
RP9				1.81	0.13	13	0.02	141	B								
LJ3	5.55	1.6	1.62			0	14.39	127		5	1.6	0.2	0.57	0.16	BA-LJ3	BA-LJ3	BA-LJ3
LP5				3.2	0.1	10	0.03	151	A								

Leadwood Access (LWA)

	LWD								Sediment							
	Jam			Piece							Depth(m)			Sample ID		
	W(m)	L(m)	D(m)	L(m)	W(cm)	Vol(m3)	Reach Dist (m)	Orient	L(m)	W(m)	D1	D2	D3	S1	S2	S3
LA-J1	2	13.5	1.5			40.50	0		14.5	2	0.2	0.68	0.92	0.78	0.66	
LA-J2	2	6	1.5			18.00	0		8	2.8	1.25	1.25	1	J2-1	J2-2	J2-3
LA-J3	5	13	2.6			169.00	10		10	6	1	1	1	J3-1	J3-2	J3-3
LA-P1				1.2	10	0.01	40	A								
LA-J4	4	15	3			180.00	100		16	3	0.8	0.6	0.8	J4-1	J4-2	J4-3
LA-P2				4	14	0.06	140	A								
LA-P3				3	18	0.08	200	A								
LA-P4				2	8	0.01	220	A								
LA-P5				1.5	9	0.01	280	C								
LA-J5	1.5	11	1			16.50	250									
LA-P6				1.5	15	0.03	290	B								
LA-J6	0.8	3.5	0.8			2.24	250									
LA-P7				7	14	0.11	310	A								
LA-P8				5	18	0.13	400	C								
LA-P9				1.7	11	0.02	400	A								
LA-J7	3	9	2			54.00	400		16	3	1.28	1.5	1.7	1.55	1.1	
LA-P10				2.3	7	0.01	440	B								
LA-P11				1.4	6	0.00	440	B								
LA-P12				2	80	1.00	440	A								
LA-P13				3.7	8	0.02	440	A								
LA-P14				2	70	0.77	460	C	7.5	1.5	0.44	1.02	1.02	1.02	1	0.8
LA-P15				3	10	0.02	470	C								
LA-P16				1.3	16	0.03	480	A								
LA-P17				2.8	8	0.01	480	C								
LA-P18				1.6	9	0.01	480	B								
LA-P19				5	7	0.02	480	A								
LA-J8	1.5	20	2.5			75.00	510		4.5	3	1.4	0.6	1.4	J8-1	J8-2	J8-3
LA-P20				6	15	0.11	530	A								
LA-P21				3.8	12	0.04	560	C								
LA-P22				4.5	25	0.22	580	C								
LA-P23				8	16	0.16	590	A								

Cherokee Landing (CL)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**W(cm)**	**Vol (m3)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
RP1				2.95	0.12	12	0.03	0	C								
RJ1	1.7	1	0.8			0	1.36	36									
RP2				2	0.15	15	0.04	26	A								
RJ2	1.3	1	0.8			0	1.04	55									
RP3				2.3	0.13	13	0.03	85	A								
RP4				1.7	0.2	20	0.05	104	B								
RP5				1.6	0.12	12	0.02	104	A								
RP6				1.3	0.38	38	0.15	105	A								
RJ3	2.8	0.93	2.12			0	5.52	111									
LP1				10.5	0.15	15	0.19	26	C								
LP2				3.54	0.295	29.5	0.24	102	B								
LP3				10.49	0.51	51	2.14	102	C	1.8	1.3	0.33	0.36	0.34	CL-LP3A	1 sample	
LP4				2.4	0.23	23	0.10	127	C	1.4	0.63	0.3	0.38	0.16	CL-LP3B	1 sample	
LP5				1.6	0.11	11	0.02	141	C								
LP6				11.3	0.48	48	2.04	166	A	1.81	0.56	0.91	1.15	1.26	CL-LP6B	CL-LP6B	CL-LP6B
LP7				1.02	0.13	13	0.01	166	B	2	1.3	0.22	0.43	0.45	CL-LP6A	CL-LP6A	CL-LP6A
LP8				1.9	0.19	19	0.05	175	A								
RJ4	1.94	1.09	1.8			0	3.81	181									
RP7				2.22	0.16	16	0.04	203	B								
RP8				5.81	0.13	13	0.08	203	D								
RJ5	1.4	1.5	1.6			0	3.36	203									
RP9				10.45	0.64	64	3.36	213	A								
LP9				2.35	0.17	17	0.05	218	B								
LP10				11.44	0.26	26	0.61	220	C								
LP11				14.5	0.26	26	0.77	248	A								
LP12				17.6	0.28	28	1.08	264	D								
LP13				13.3	0.23	23	0.55	264	B								
LJ1	1.9	3.7	1.35			0	9.49	264		4.2	1.2	0.51	0.9	0.25	LJ1	LJ1	LJ1
LP14				8.45	0.17	17	0.19	264	A								
RP10				2.1	0.13	13	0.03	265	A								
RP11				4.5	0.11	11	0.04	265	C								
LP15				7	0.58	58	1.85	345	A								
RP12				3.23	0.26	26	0.17	365	D								
RP13				4.2	0.46	46	0.70	365	D								

Blackwell (BW)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**m**	**Vol (m3)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
RJ1	1.8	4.2	0.9				6.80	0									
RJ2	1.5	1.9	1.2				3.42	0		3.3	1.1	1.8	1.7	1.16	RJ2	RJ2	RJ2
RP1				4.41	0.13	13	0.06	8	A								
RP2				1.39	0.23	23	0.06	2	A								
RP3				1.2	0.13	13	0.02	6	A								
RP4				1.04	0.22	22	0.04	21	B								
RP5				2.5	0.12	12	0.03	22	A								
RP6				1	0.11	11	0.01	23	D								
RJ3	1.7	2.4	0.85				3.47	40		2.5	0.62	1.3	1.1	0.85	RJ3	RJ3	RJ3
RP7				9.9	0.2	20	0.31	55	A								
RP8				2.08	0.32	32	0.17	62	D								
RP9				1.22	0.19	19	0.03	68	C								
RP10				1.12	0.21	21	0.04	62	B								
RP11				5.8	0.14	14	0.09	68	A								
RJ4	2.7	6.4	2.2				38.02	68									
RP12				1.66	0.15	15	0.03	110	C								
RP13				3.4	0.19	19	0.10	87	D								
LJ1	2.4	2.4	2.5				14.40	40									
RJ6	3	15	2				90.00	40									
RP14				2	3	300	14.13	122	A								
RJ7	1.4	10.2	2.3				32.84	122									
RJ8	0.7	1.5	0.8				0.84	137									
RJ9	3.8	15.2	2.2				127.07	137									
RJ10	1	3.6	0.9				3.24	122									
RP16				1.7	0.32	32	0.14	122	A								
RP17				6.1	0.18	18	0.16	162	D								
RP18				8.1	0.25	25	0.40	162	A								
RP19				5.8	0.15	15	0.10	162	C								
RP20				5.2	0.3	30	0.37	182	A								
RP21				2.7	0.21	21	0.09	182	D								
RP22				8.4	0.2	20	0.26	192	D								
RP23				15	0.33	33	1.28	221	A								
RP24				31.8	0.45	45	5.06	240	D								

Mammoth Access (MA)

	LWD								Sediment Deposit							
	Jam			Piece							Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(cm)**	**Vol (m3)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
MA-J1	1	17	2			34.00	0		15	3	0.5	0.4	0.2	J1-1	J1-2	J1-3
MA-P1				5	8	0.03	20	A								
MA-P2				9	10	0.07	30	A								
MA-P3				9	12	0.10	30	A								
MA-P4				3	9	0.02	50	C								
MA-P5				9.5	15	0.17	90	C								
MA-J2	0.5	8	0.6			2.40	170									
				2.5	8	0.01	0									
MA-P6				2	12	0.02	190	A								
MA-J3	3.5	23	1.5			120.8	200		4	2	0.9	0.8	0.5	J3-1	J3-2	J3-3
MA-P8				2.3	13	0.03	230	A								
MA-P9				2.2	8	0.01	270	A								
MA-P10				13	40	1.63	350	C								
MA-P11				3.6	12	0.04	350	C								
MA-P12				4	9	0.03	350	B								
MA-P13				3.6	21	0.12	350	A								
MA-P14				4	12	0.05	350	A								
MA-P15				4.5	10	0.04	350	C								
MA-J4	3.5	11	1			38.50	380									
MA-P16				1.4	12	0.02	360	B								
MA-P17				5.2	11	0.05	360	A								
MA-P18				4.1	30	0.29	360	A								

Browns Ford Access(BFA)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(cm)**	**Vol (m3)**	**Reach dist (km)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
						292.5											
BF-J1	5	19.5	3			0		0		16	10	1.2	0.95	0.68			
BF-P1				15	60	4.24	0	0									
BF-P2				7.5	12	0.08	0	0									
BF-P3				3.6	26	0.19	0	0									
BF-P4				5.2	15	0.09	0.01	10									
BF-P5				11.6	78	5.54	0.02	20									
BF-P6				4	19	0.11	0.02	20									
BF-P7				3.6	10	0.03	0.05	50									
BF-P8				2.2	15	0.04	0.05	50									
BF-P9				2.1	14	0.03	0.05	50									
BF-P10				3.8	46	0.63	0.05	50									
BF-P11				10.8	34	0.98	0.05	50		8	8	0.5	1.6	1.68	P11-1US	P11-2US	P11-3US
						0.00		0		7	3.4	1.6	1.3	1.3	P11-1DS	P11-2DS	P11-3DS
						0.00		0		10	5.5	0.86	1.04	1.12	1.1	0.88	0.62
BF-P12				1.8	9	0.01	0.07	70									
BF-P13				3.9	9	0.02	0.07	70									
BF-P14				13	38	1.47	0.07	70									
BF-P15				4.4	15	0.08	0.08	80									
BF-P16				1.3	21	0.05	0.08	80									
BF-P17				6.2	46	1.03	0.08	80									
BF-P18				6.1	14	0.09	0.08	80									
BF-P19				2.8	28	0.17	0.08	80									
BF-P20				4.3	17	0.10	0.1	100									
BF-P21				3.6	16	0.07	0.1	100									
BF-P22				1.9	17	0.04	0.14	140									
BF-P23				2.8	11	0.03	0.14	140									
BF-P24				3.4	9	0.02	0.14	140									
BF-P25				6.1	31	0.46	0.15	150		7	3	0.7	0.7	0.5	P25-1	P25-2	P25-3
BF-P26				4.5	9	0.03	0.14	140									
BF-P27				2.2	8	0.01	0.18	180									
BF-P28				6.8	14	0.10	0.18	180									
BF-J2	2.2	9	2.5			49.50	0.21	210									
BF-P29				3.7	32	0.30	0.18	180									
BF-P30				3.4	8	0.02	0.21	210									
BF-P31				1.8	10	0.01	0.21	210									
BF-P32				25.4	38	2.88	0.21	210									
BF-P33				19.5	30	1.38	0.23	230									
BF-P34				16.2	66	5.54	0.23	230									

Browns Ford, Cont'd.

				11.2	32	0.90	0.25	250	
BF-P36				1.2	11	0.01	0.25	250	
BF-P37				2.3	9	0.01	0.25	250	
BF-P38				7.2	24	0.33	0.27	270	
BF-J3	1.2	14.1	0.5			8.46	0.28	280	
BF-P39				3.2	15	0.06	0.3	300	
BF-P40				3.8	12	0.04	0.3	300	
BF-P41				4.2	10	0.03	0.3	300	
BF-J4	1	2.8	0.8			2.24	0.31	310	

Morse Mill (MM)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**Vol (m3)**	**Reach dist (km)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
MM-P1				11.5	4	0.01											
MM-P2				3.2	9	0.02											
MM-P3				3	30	0.21											
MM-P4				3.1	12	0.04											
MM-P5				3.2	9	0.02											
MM-P6				2.7	70	1.04											
MM-P7				2.1	80	1.06											
MM-P8				4.5	45	0.72											
MM-J1	0.8	26	0.6			12.48				5.2	1.4	0.65	0.65	0.65	J1-1	J1-2	J1-3
MM-P9				2.2	32	0.18	0	0									
MM-P10				3.8	28	0.23	0	0									
MM-P11				4.4	34	0.40	0	0									
MM-P12				9.2	26	0.49	0	0									
MM-P13				2.5	16	0.05	0	0									
MM-P14				2.3	16	0.05	0.03	30									
MM-J2	2	15	2.2			66.00	0.03	30									
MM-P15				2	12	0.02	0.03	30									
MM-P16				3	8	0.02	0.03	30									
MM-P17				1.8	8	0.01	0.04	40									
MM-J3	1.5	2.8	1.1			4.62	0.04	40									
MM-P18				4	24	0.18	0.05	50									
MM-P19				5.2	32	0.42	0.05	50									
MM-P20				3.4	27	0.19	0.05	50									
MM-P21				4.5	9	0.03	0.05	50									
MM-J4	0.5	5.1	0.4			1.02	0.09	90									
MM-P22				5.4	14	0.08	0.09	90									
MM-P23				14	32	1.13	0.1	100									
MM-P24				8	34	0.73	0.1	100									
MM-J5	1	3	0.9			2.70	0.15	150									
MM-P25				11.3	31	0.85	0.15	150									
MM-P26				24	23	1.00	0.17	170									
MM-P27				3.2	16	0.06	0.18	180									
MM-P28				5.3	13	0.07	0.19	190									
MM-P29				2.2	46	0.37	0.23	230									
MM-J6	0.5	24	0.8			9.60	0.26	260		22	2	0.8	0.9	1.2	J6-1	J6-2	J6-3
MM-P30				3.2	12	0.04	0.28	280									
MM-P31				4.1	15	0.07	0.29	290									
MM-P32				3.3	34	0.30	0.31	310									
MM-J7	2.2	11.2	0.9			22.18	0.32	320		5.3	4.2	1.5	1.6	1.3	J7-1	J7-2	J7-3

Morse Mill(MM) Cont'd.

MM-P33		4.5	44	0.68	0.33	330
MM-P34		3.5	16	0.07	0.33	330
MM-P35		4.3	58	1.14	0.37	370
MM-P36		1.6	9	0.01	0.37	370
MM-P37		12	40	1.51	0.54	540

Cedar Hill (CH)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**W(cm)**	**Vol (m3)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
RP1				15.3	0.38	38	1.73	0	D	2.4	3.3	1.88	1.77	1.79	RP1	RP1	RP1
RP2				5.1	0.11	11	0.05	0	C								
LP1				4.72	0.11	11	0.04	5	B								
LP2				1.22	0.12	12	0.01	0	A								
RP3				22.96	0.46	46	3.81	71	C								
RP4				18.9	0.23	23	0.78	67	B								
RP5				3.91	0.16	16	0.08	133	A								
RP6				13.8	0.2	20	0.43	126	A								
LP3				8.3	0.35	35	0.80	126	A								
LP4				4	0.22	22	0.15	133	C								
LP5				3.5	0.2	20	0.11	150	D								
LP6				14	0.3	30	0.99	211	D								
RP7				9.2	0.32	32	0.74	172	A								
RP8				2.8	0.14	14	0.04	232	C								
RJ1	2.7	1.15	0.8			0	2.48	232									
LP7				2.45	0.24	24	0.11	267	B								
LP8				1.2	0.2	20	0.04	274	B								
LP9				7	0.15	15	0.12	302	D								
LP10				3.1	0.13	13	0.04	320	C								
RP9				3.6	0.17	17	0.08	350	B								
RP10				2.68	0.15	15	0.05	349	C								
RP11				10.8	0.14	14	0.17	349	D								
RP12				5.97	0.14	14	0.09	358	A								

Rockford Beach (RB)

	LWD								Sediment Deposit								
	Jam			Piece								Depth (m)			Sample ID		
	W(m)	**L(m)**	**D(m)**	**L(m)**	**W(m)**	**Vol (m3)**	**Reach dist (km)**	**Reach dist (m)**	**Orient**	**L(m)**	**W(m)**	**D1**	**D2**	**D3**	**S1**	**S2**	**S3**
RB-P1				2.2	16	0.04	0	0									
RB-P2				18	50	3.53	0	0									
RB-P3				4.2	70	1.62	0	0									
RB-P4				2.4	33	0.21	0	0									
RB-P5				1.5	8	0.01	0	0									
RB-P6				1.4	9	0.01	0.01	10									
RB-P7				2.7	8	0.01	0.03	30									
RB-P8				2	9	0.01	0.03	30									
RB-P9				2	18	0.05	0.03	30									
RB-P10				3	8	0.02	0.04	40									
RB-P11				3.2	55	0.76	0.04	40									
RB-P12				10.5	38	1.19	0.05	50									
RB-P13				1.7	9	0.01	0.05	50									
RB-P14				6.4	11	0.06	0.05	50									
RB-J1	1	4	1			4.00	0.06	60									
RB-J2	1	10.5	2.5			26.25	0.07	70									
RB-P15				4.2	20	0.13	0.08	80									
RB-P16				2.8	32	0.23	0.08	80									
RB-J3	2	7	2			28.00	0.08	80		11	2.5	1.2	1.2	1.2	J3-1	J3-2	J3-3
RB-P17				3.3	36	0.34	0.1	100									
RB-P18				2.1	13	0.03	0.1	100									
RB-P19				1.5	28	0.09	0.1	100									
RB-P20				1.7	13	0.02	0.1	100									
RB-P21				5.5	22	0.21	0.1	100									
RB-J4	1.5	3.4	0.8			4.08	0.1	100									
RB-J5	0.8	2.5	0.6			1.20	0.1	100									
RB-P22				4.8	32	0.39	0.12	120									
RB-P23				3	30	0.21	0.12	120									
RB-P24				1.6	13.5	0.02	0.08	80									
RB-P25				1.2	11	0.01	0.08	80									
RB-P26				1.6	10.5	0.01	0.08	80									
RB-P27				1.9	24	0.09	0.1	100									
RB-P28				2.8	8	0.01	0.1	100									
RB-P29				3	8	0.02	0.1	100									
RB-J6	2	10.5	1.5			31.50	0.12	120		15.3	2	0.9	1	1	J6-1	J6-2	J6-3
RB-P30				1.8	10	0.01	0.16	160		7.2	3.2	0.9	1.5	1.5	P30-1	P30-2	P30-3
RB-P31				1	9	0.01	0.16	160									
RB-P32				2	17	0.05	0.16	160									
RB-P33				3.2	12	0.04	0.18	180									
RB-P34				3	15	0.05	0.19	190									
RB-J7	1.5	22.5	1.5			50.63	0.3	300									

Vita

Derek J. Martin earned a Bachelor of Science degree in Biology with a concentration in Ecology from Lake Superior State University, in Sault Ste. Marie, Michigan, in 2002. He received a Master of Science degree from the Department of Geography, Geology, and Planning from Missouri State University in 2005. His thesis research involved the use of Geographic Information Systems and historical aerial photographs to characterize patterns of channel planform change at sites along the Current River, and the Jacks Fork of the Current River in the Ozarks National Scencic Riverways, Missouri. After working for two years as a GIS technician for the Upper Mississippi River Basin Association in St. Paul, Minnesota, Derek returned to Missouri State University to work as a Research Specialist for the Ozarks Environmental and Water Resources Institute (OEWRI). He served in that position for three years before enrolling in the Ph.D. program in Geography at The University of Tennessee. In 2014 he was awarded the Doctor of Philosophy degree in Geography by the University of Tennessee. During his time at the University of Tennessee, he served as a Graduate Teaching Assistant, a Graduate Teaching Associate, a Research Assistant, and received numerous departmental awards including the Robert G. Long Outstanding Ph.D. Student Award. Derek will relocate to Boone, North Carolina where he has accepted a position as an Assistant Professor in the Department of Geography and Planning at Appalachian State University.