This is to certify that the

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ECOLOGICAL IMPLICATIONS OF COARSE WOODY DEBRIS
IN LOW GRADIENT MIDWESTERN STREAMS

presented by

Lucinda Ballard Johnson

has been accepted towards fulfillment
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Thomas M. Burton
Major professor

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ECOLOGICAL IMPLICATIONS OF COARSE WOODY DEBRIS IN LOW GRADIENT MIDWESTERN STREAMS

By

Lucinda Ballard Johnson

A DISSERTATION

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ABSTRACT

ECOLOGICAL IMPLICATIONS OF COARSE WOODY DEBRIS IN LOW GRADIENT MIDWESTERN STREAMS

By

Lucinda Ballard Johnson

Coarse woody debris (CWD) is an important component of small to medium streams in forested regions, directly influencing stream geomorphology as well as many ecosystem properties and processes. Little is known about the influence of the landscape context on standing stocks of CWD. The goals of this dissertation are to: 1) characterize the abundance, size, and distribution of CWD in low gradient streams of developed watersheds; 2) quantify the relative influence of reach- and catchment-scale factors on the abundance, distribution, and retention of CWD, and 3) examine the relationships between CWD, channel form, habitat structure, macroinvertebrate community structure and macroinvertebrate species traits.

CWD standing stocks in these Michigan streams are small compared with forested streams, and strong interactions between land use and surficial geology influence its abundance and distribution. CWD accumulation density and distribution are well predicted by the environmental variables measured in this study. Factors at the local scale (e.g., bank-full width, percent of open canopy, and riparian vegetation type) have a large influence on the density and distribution of debris accumulations, but only a

moderate influence on CWD abundance and volume. In contrast, landscape features including link number, percent urban land use in the catchment, and topographic heterogeneity, exert greater control over CWD abundance. The debris accumulations in these Midwestern streams are smaller and contain fewer and smaller logs than streams of forested regions. Debris accumulations do not play a physical role in modifying channel morphology, as do debris accumulations in forested landscapes.

Although woody debris is not abundant in these streams, it is one of the most important habitats for macroinvertebrates in the streams of the Saginaw Basin. Since woody debris can occur in both fast and slack water, the taxa found in association with wood habitats span a range of current preferences, as well as functional and habit traits. The patterns in the distribution of habit and functional traits within wood habitats suggests that these traits may vary with the location of woody debris in the channel relative to the flow regime.

Log retention and recruitment is in dynamic equilibrium, with the logs exhibiting the greatest movement being the smaller logs. Approximately 50% of the logs at a site were replaced between October 1995 and June 1996 following a flood with a return interval of approximately 5 years. Although the number of logs present before and after the flood remained approximately equal, log volume was greater before the flood than after. Management efforts to retain woody debris in streams must consider both local as well as landscape-scale factors.

Dedication

To Randy, thank you for your love and support throughout this endeavor, and my parents, Margaret and Martin Johnson for providing the incentive and love of learning.

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Acknowledgments

I sincerely acknowledge the contributions of Carl Richards and George Host for their collaborative efforts and encouragement throughout this project. Roger Haro and Dan Breneman contributed extensively to the collection of stream habitat data, and the compilation / oversight of stream databases. I also wish to acknowledge the valuable contribution of Tom Sampson in the collection of the woody debris data in 1996. Connie Host, Dan Fitzpatrick, Shawn Boeser, and Gerry Sjerven were all instrumental in assembling spatial data used in this project and performing relevant analyses when necessary. Tom Hollenhorst and Amos Ziegler were extremely helpful in assisting with preparation of graphics. I also gratefully acknowledge the assistance of Greg Grunwald with the interpretation of the regression results. I am grateful to Dr. Gerald Niemi for encouraging me to embark on this endeavor and providing the institutional and moral support. I also wish to extend my appreciation to Thomas Burton (dissertation advisor), Stuart Gage, Donald Hall, and Richard Merritt for their support and advice throughout my program at Michigan State University. Funding for this project was provided by a grant from the Environmental Protection Agency to Carl Richards, myself, and George Host (Grant Number CR-822043-01-0), with additional monetary assistance from the Department of Zoology at Michigan State University. The Natural Resources Research Institute of the University of Minnesota, Duluth provided salary support during my graduate program. Last, but not least, my husband Randall Hicks is gratefully acknowledged for his love and support during this effort.

Table of Contents

List of Tables

T

Ta

Ta-

List of Figures

List of Abbreviations and Symbols

CPOM = coarse articulate organic matter

CWD = coarse woody debris

Lac/Ag = lacustrine / agricultural

Lac/Mix = lacustrine / mixed

Mor/Ag = morainal / agricultural

Mor/Mix = morainal / mixed

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Chapter 1

INTRODUCTION

For decades, streams managers regarded woody debris in the same vein as beavers and old tires-- objects that must therefore be removed from stream channels because they are either unsightly or impede flow. Interest in angling and stream restoration has highlighted the role of woody debris in controlling / influencing many physical, chemical, and biological characteristics of stream ecosystems. Coarse woody debris (CWD; defined variously as wood $\geq$ 5 or $\geq$ 10 cm in diameter and $\geq$ 1 to 2 m in length), plays an important role in shaping stream channel structure by altering channel pattern and dimensions, and creating plunge pools and backwaters (e.g., Swanson, et al. 1976, Bilby 1984, Nakamura and Swanson 1993, Richmond and Fausch 1995). These alterations in channel morphology affect flow processes, thereby influencing hydraulic retention (e.g., Trotter 1990, Ehrman and Lamberti 1992, Raikow, et al. 1995), sediment transport and storage (e.g., Bilby 1981, MacDonald and Keller 1987, Bilby and Ward 1989, Nakamura and Swanson 1993), bank erosion (e.g., Murgatroyd and Ternan 1983, Shields and Smith 1992, Smith, et al. 1993), and timing of peak flood events (MacDonald, et al. 1982, Gregory, et al. 1985). While most physical alterations by CWD are found in low-order streams, historic records reveal significant channel alterations in large rivers as well (e.g., Triska 1984).

Physical and chemical alterations to the channel and water column induce a cascade of effects on ecosystem processes that affect primary and secondary production,

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and other trophic interactions. Debris accumulations trap organic matter, and their removal results in a net export of dissolved organic carbon (DOC), fine particulate organic matter (FPOM) and coarse particulate organic matter (CPOM) (Bilby and Likens 1980, Bilby 1981). Channels with cobbles and coarse woody debris (which behave as periphyton substrates) show higher nutrient uptake (Aumen, et al. 1990) and thus, presumably also have smaller spiraling distances (Newbold, et al. 1982). Fish, invertebrates (Angermeier and Karr 1984, Lehtinen, et al. 1997) and the biofilm community (Shearer and Webster 1991, Hax and Golladay 1997) benefit from increased habitat heterogeneity in addition to CPOM retention. Fish respond positively to the presence of coarse woody debris accumulations for cover, flow and predation refugia, and increased food availability (e.g., Angermeier and Karr 1984, McMahon and Hartmen 1989, Everett and Ruiz 1993, Culp et al. 1996). The invertebrate community responds to the CPOM energy source by shifting feeding functional groups from scrapers and filter feeders to collectors and predators (Anderson, et al. 1978, Benke, et al. 1984, Smock, et al. 1989, Wallace, et al. 1995). Particularly in areas with unstable substrates, CWD provides a stable substrate for both primary and secondary production (Benke, et al. 1984, Smock, et al. 1989, Hax and Golladay 1997). Stream sections with added logs exhibit significantly greater secondary production than do sections without log additions (Wallace, et al. 1995). In short, CWD positively influences many stream ecosystem processes (see recent reviews by Harmon, et al. 1986, Gregory and Davis 1992, Gurnell, et al. 1995; Table 2-1).

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In many regions of the United States coarse woody debris was historically a prominent feature in streams, such that log jams stretched for kilometers on both small and larger streams (Swanson, et al. 1976, Triska 1984, Maser and Sedell 1994). Debris removal was originally initiated to provide unobstructed waterways for navigation and transport corridors for harvested logs. In 1776 the U.S. Congress appropriated money to clear driftwood from streams and rivers to improve navigation, beginning with the Mississippi River. Woody debris removal remains an active role of the U.S. Army Corps of Engineers (Harmon, et al. 1986), and is one of the primary roles of County Drain Commissioners (locally elected officials charged with creation and maintenance of an extensive network of drainage ditches) in the state of Michigan.

Coarse woody debris abundance in temperate stream ecosystems is regulated by a complex set of factors that act on the source of the wood itself, its delivery to the channel, and lastly, on the myriad of factors that control its retention and mobility once it is delivered to the channel. At regional scales, geomorphic features have regulated the original vegetation of the landscape (Grimm 1984, Host and Pregitzer 1992), as well as the historical and current land use/land cover patterns within the region. Both historic and current land management factors in the riparian zone and the floodplain influence the supply of the CWD (Hogan 1986, Murphy and Koski 1989, Evans, et al.1993, Ralph, et al. 1994). Forested landscapes are increasingly fragmented by forest harvest as well as land conversion for agricultural production and urban development. Silvicultural practices alter species composition, number, and size distribution of trees in the upland,

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and thus modify the potential source and input rates of CWD, particularly in small to medium-sized streams (Bilby 1984, McDade, et al. 1990, Fetherston, et al. 1995). In agricultural and urban areas potential sources of woody debris as well as the stream retention capacity are altered by management practices such as grazing, landscaping, riparian vegetation thinning or removal, dredging and channelization. Although these management activities can undoubtedly reduce the potential supply of in-stream CWD, current riparian zone vegetation may not accurately reflect standing stocks of CWD. A highly retentive stream channel can contain very old wood (Keller and Tally 1979, Murphy and Koski 1989), which can predate the age of the current riparian vegetation (Swanson and Lienkaemper 1978, Evans et al. 1993).

The riparian zone and the land-water ecotone mediate inputs of sediment, nutrients, and particulate organic matter to streams, in addition to providing other important ecosystem functions (Gregory, et al. 1991). The primary sources of CWD in streams are derived from natural mortality, fire, disease, insect damage, ice/snow loading, and wind-throw damage to trees in the riparian zone or uplands adjacent to the stream (Keller and Swanson 1979). Processes such as mass soil wasting, bank undercutting and erosion, and flooding transport this material into the stream. Beaver may be the primary vector transporting large volumes of CWD to the channel in some systems (Naiman, et al. 1986, Maser and Sedell 1994). Alteration of the hydrologic regime resulting from stream channelization, wetland filling, or urbanization frequently results in increased bank erosion, one of the primary mechanisms of CWD input to low-gradient streams (Keller and Sw

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and Swanson 1979; Davis and Gregory 1994). Erosion processes are themselves regulated by geologic factors (e.g., soil type, topography), vegetation cover type, and hydrologic regime, in addition to anthropogenic factors including grazing, forest harvest, construction, and agriculture.

Once wood is introduced to the channel it is either retained by obstructions in the channel, or by the channel itself, if the log is large relative to the size of the channel (Keller and Swanson, 1979, Keller and Talley 1979). A positive feedback loop is initiated when wood is retained by an obstruction, resulting in debris jams that continue to assimilate wood until the accumulation fails due to high flow or some other factor. Morphological changes in the channel that are attributed to CWD, including plunge pool formation, lateral adjustments, sediment and organic matter retention, can themselves influence CWD mobility and retention. For example, decreased flow velocity due to pool formation will result in decreased stream power and capacity to transport CWD (Braudrick et al. 1997). Channel bars resulting from sediment and organic matter retention themselves form obstacles for CWD.

Since CWD fundamentally influences both the structure and function of many streams, identifying the myriad factors that regulate its abundance and distribution is essential for understanding the fundamental factors regulating stream ecosystems. The role of coarse woody debris in high- and low-gradient catchments has been well studied (Table 2-1). Stream restoration activities that attempt to increase habitat heterogeneity to enhan

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enhance fish and invertebrate production frequently use log structures anchored in the channel (Hunter, 1991). These structures are subject to failure, and can cause or exacerbate existing problems (Beschta and Platts 1986). Recent studies have attempted to examine the influence of log placement on the channel and the biota (Hilderbrand, et al. 1997). Studies such as these fail to account for larger scale factors that influence both the input and retention of CWD in streams. Landscape-scale factors such as land use and surficial geology influence the abundance of woody debris found in stream channels (Ralph, et al. 1994; Richards, et al. 1996) and undoubtedly also play a role in mediating the impact of disturbance events that influence the export of CWD and smaller organic matter fragments. By examining the factors influencing large woody debris at a range of spatial scales, the extent to which local and regional factors regulate the abundance and distribution of CWD can be discriminated.

Context

This study is part of a larger study by researchers (Carl Richards, George Host, and myself) at the University of Minnesota, Duluth to develop ecological indicators for Midwestern streams. Ecological criteria are numeric or descriptive means by which the condition of an ecosystem can be described with respect to designated water resources. The use of ecological criteria is tied to the concept of ecological integrity, which is the condition of aquatic ecosystems in unimpaired waterbodies. The concept of ecological criteria is analogous to biocriteria (Barbour, et al. 1994) with the exception that ecological criteria refer to the combined biological, physical, and chemical attributes of ecosyst

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ecosystems essential for maintaining sustained function, whereas biocriteria refer only to the biotic communities that inhabit water bodies. Ecological criteria constitute a wide array of parameters crucial to the assessment, maintenance, and restoration of aquatic ecosystems. The development of ecological criteria for streams and their watersheds requires the identification of a select group of parameters that most strongly influence stream ecosystems. Such criteria should be capable of defining reference conditions typical of unimpaired streams or streams with minimal anthropogenic stresses as well as be responsive to ecological degradation found within the geographic region of interest.

The primary objective of the overall study was to develop watershed-scale ecological criteria that quantify landscape and habitat factors that most strongly influenced stream ecosystem integrity. In particular, we examined the influence of watershed-scale attributes such as landuse/cover patterns and geomorphology as determinants of the fine-scale processes and conditions that impact the ecological integrity of streams.

Previous work to identify biological criteria in the Saginaw Basin in Michigan demonstrated the influence of Quaternary geology and land use (especially rowcrop agriculture) as dominant landscape features that influenced habitat and macroinvertebrate community structure (Richards, et al. 1996). In addition, CWD was identified as one of the important reach-scale factors influencing the macroinvertebrate species traits (Richards, et al. 1997). Since CWD was not a dominant feature in most of the streams in the stuc

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the study region, these finding were somewhat surprising. As a result, the project to develop ecological criteria provided an opportunity to examine in greater detail the factors contributing to the abundance and distribution of CWD in these streams, and to quantify the relationship between CWD, habitat structure, and community composition.

Overview

The goals of the coarse woody debris project around which this dissertation is based are to: 1) characterize the abundance, size, and distribution of CWD in low gradient streams of developed watersheds; 2) quantify the relative influence of reach- and catchment-scale factors on the abundance, distribution, and retention of CWD, and 3) examine the relationships between CWD, channel form, habitat structure, macroinvertebrate community structure and macroinvertebrate species traits. Specific hypotheses that are addressed are:

1. CWD abundance and distribution is controlled primarily by local factors (e.g., riparian zone structure and composition, channel features).

    Local factors controlling CWD abundance and distribution are themselves controlled by factors at larger spatial scales (e.g., dominant land use, Quaternary geology, topography, landscape fragmentation).

2. The number, type, and size of debris accumulations are a function of channel dimensions and topography, as well as landscape characteristics.

Debris accumulation type is a function of channel form, which is controlled by landscape factors.

3. Stocks of CWD within the stream reach positively influence channel form, habitat structure, macroinvertebrate community structure, and macroinvertebrate species traits.
4. CWD retention is influenced by log size, channel dimensions, and flow.

This dissertation is composed of five chapters including the Introduction: 1) Channel, Riparian, and Landscape Features as Predictors of Coarse Woody Debris Abundance in Midwestern Streams, 2) Coarse Woody Debris Accumulations in Low Gradient Streams: Relation to Local and Landscape Features, 3) Coarse Woody Debris Retention and Recruitment in Low Gradient, Agricultural Watersheds, and 4) Macroinvertebrate Community Structure and Function Associated with Coarse Woody Debris in Low Gradient, Agricultural Streams. The goals of Chapter 2 are to: characterize the abundance, size and distribution of CWD in low gradient streams within streams in a highly developed landscape, and quantify the relative influence of reach-, riparian-, and landscape-scale factors on the abundance and distribution of CWD. Coarse woody debris has been studied primarily in mountainous streams of the Pacific Northwest; very few studies of CWD have been conducted in non-forested streams. This study is intended to fill this research gap, and to address hypotheses concerning the regulation of CWD by factors operating at different spatial scales.

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In Chapter 3 the number and distribution of four debris accumulations types were quantified with respect to local, riparian and landscape variables. Debris accumulations, rather than individual logs, are often the agent influencing channel geomorphology. In contrast to forested streams, debris accumulations take on many different forms in the Saginaw Basin. Many streams are characterized by thick overhanging vegetation in the form of willow or alder. In many streams these structures are the only features within the channel that can function as flow refugia, habitat, or as geomorphic agents. Debris accumulation types, including overhanging vegetation with trapped organic debris, root wads with trapped organic debris, loose accumulations of logs, and log/snag jams were examined in this chapter (Figure 3-2).

Chapter 4 reports the results of a log tagging experiment, conducted to examine CWD retention in these streams. Individual logs within a reach were tagged and turnover of these logs from the reach after a winter and associated spring floods was quantified. Log size and volume, as well as channel dimensions and flow characteristics were used to predict log retention and movement.

The role of CWD in highly disturbed agricultural streams is largely unknown. Chapter 5 assesses one potential role of CWD: the influence of CWD on the structure and function of the macroinvertebrate community. The community of macroinvertebrates unique to CWD were characterized, and the functional characteristics of the taxa that are unique to the woody debris habitat were identified.

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Study Area

The Saginaw Bay catchment of Lake Huron encompasses a 16,317 km^2 region (Figure 1-1), characterized by sand and clay-dominated lowlands rimmed by coarse-textured glacial features such as ground moraines and outwash plains (Figure 1-2). The study region is contained within two major ecoregions as defined by Omernik and Gallant (1986): the Southern Michigan/Northern Indiana Till Plains and the Huron/Erie Lake Plain. Each is subdivided into two sub-regions. Soils in the lake plain are dominated by medium- and fine-textured loams ranging to clays, with sand in the outwash plains and channels. These clay regions are extensively drained by artificial drainage and tile systems. The periphery of the basin contains many coarse textured glacial features such as ground moraines and outwash plains. The till plain exhibits the greatest variation in basin topography and contains a high percentage of forested land intermingled with agricultural land and old fields (Figure 1-3); elevations average about 278 m (Figure 1-4). The entire drainage was logged for white pine and hemlock between 1840 and 1900, and forests of the region now consist primarily of second growth hardwood species.

Figure 1.1. Study area in central Michigan, U.S.A.

Figure 1-1. Study area in central Michigan, U.S.A.

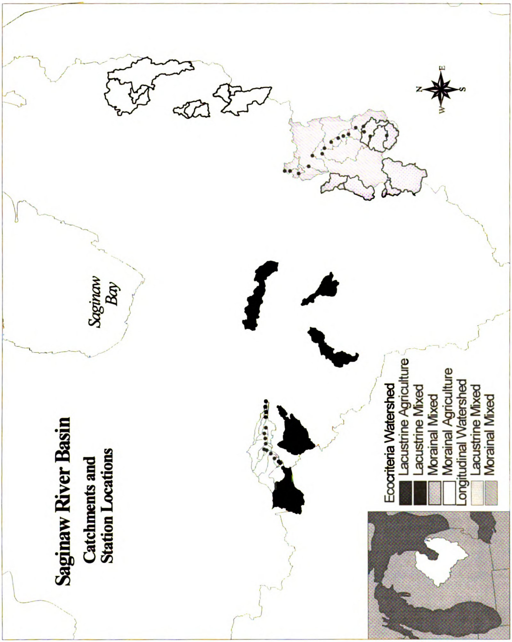
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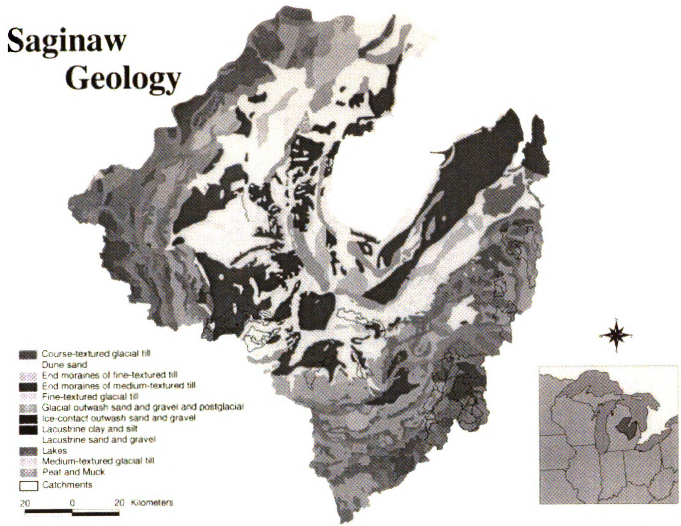
Figure 1-2. Quaternary geology in the Saginaw Basin, Michigan (from Farrand and Bell 1984). Albers projection.

Figure 1-2. Quaternary geology in the Saginaw Basin, Michigan (from Farrand and Bell 1984). Albers projection.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Fine-textured glacial till
Glacial outwash sand and gravel and postglacial
Ice-contact outwash sand and gravel
Lacustrine clay and silt
Lacustrine sand and gravel
Lakes
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Figure 1-4. Land use / cover in the Saginaw Basin, Michigan (from the MI Department of Natural Resources, MIRIS database). Albers projection.

Figure 1-3. Land use / cover in the Saginaw Basin, Michigan (from the MI Department of Natural Resources, MIRIS database). Albers projection.

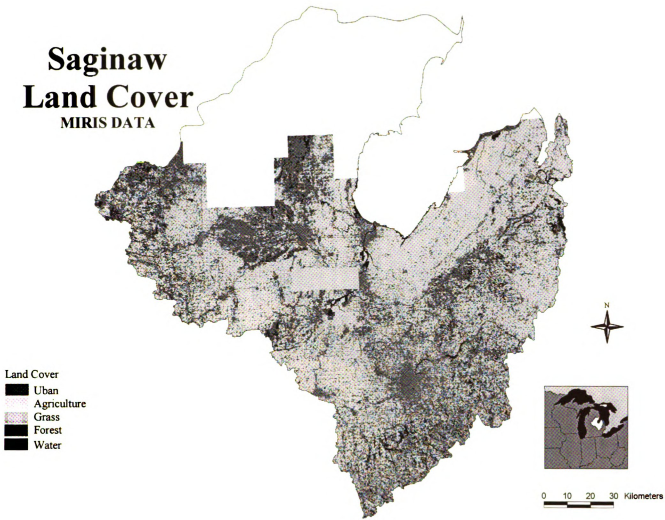
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Figure 1-4. Elevation across the Saginaw Basin, Michigan (from USGS Digital Elevation Model data). Elevations ranges from 175 - 468 m. Albers projection.

Figure 1-4. Elevation across the Saginaw Basin, Michigan (from USGS Digital Elevation Model data). Elevations ranges from 175 - 468 m. Albers projection.

Saginaw
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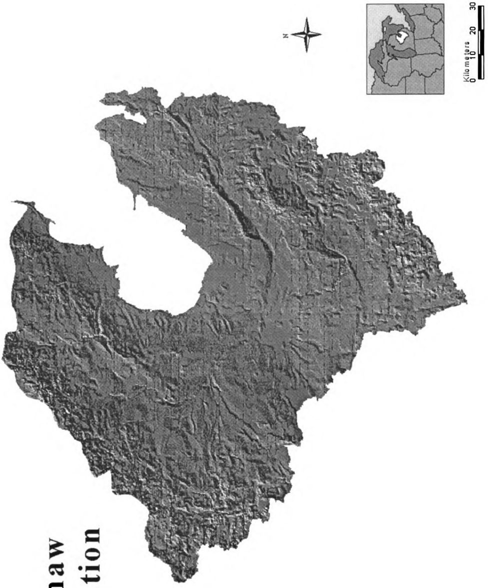

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CHAPTER 2

CHANNEL, RIPARIAN AND LANDSCAPE FEATURES AS PREDICTORS OF COARSE WOODY DEBRIS ABUNDANCE IN MIDWESTERN STREAMS

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Abstract

Coarse woody debris (CWD) is an important component of small to medium streams in forested regions, directly influencing stream geomorphology as well as many ecosystem properties and processes. Current land management practices can directly and indirectly influence the abundance of wood in streams, especially in highly developed regions. The goals of this chapter are to: 1) characterize the abundance, size, and distribution of CWD in low gradient streams in developed landscapes, and 2) quantify the relative influence of reach- and catchment-scale factors on the abundance and distribution of CWD.

Strong interactions between land use and surficial geology occur across the study area and influence the standing stocks and distributions of CWD. CWD accumulation density and distribution are well predicted by the environmental variables measured in this study. Factors at the local scale (e.g., bank-full width, percent of open canopy, and riparian vegetation type) have a large influence on the density and distribution of debris accumulations, but only a moderate influence on CWD abundance and volume. In contrast, landscape features including link number, percent urban land use in the catchment, and topographic heterogeneity, exert greater control over CWD abundance. The differences in the factors predicting CWD standing stocks versus accumulation densities are probably related to the local-scale processes that entrain wood into debris accumulations.

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Introduction

Coarse woody debris (CWD) is an important component of small to medium size streams in forested regions, directly influencing stream geomorphology as well as many ecosystem properties and processes (e.g., Harmon, et al. 1986, Gregory and Davis 1992, Gurnell, et al. 1995; Table 2-1). Woody debris exerts control over the structure of aquatic habitats by impeding flow, thereby increasing flow heterogeneity in the channel, influencing the pool-riffle sequence, erosional processes, channel dimensions, and deposition and retention of sediment and organic matter in the channel. Habitats created by CWD are varied, including plunge pools, backwaters and eddies, as well as the interstices of debris dams and individual logs. These habitats are critical for fish as well as invertebrate species (Angermeier and Karr 1984, Benke, et al. 1985, Beechie and Sibley 1997), providing flow and predation refugia for fish (Everett and Ruiz 1993), oviposition and pupation sites (Dudley and Anderson 1982), a feeding platform for invertebrates, and a substrate for biofilm production (Shearer and Webster 1991, Hax and Golladay 1997). The structure and dynamics of physical habitat in streams (Southwood 1977) and potential sources of colonizers (Gore 1982) regulate the composition and function of stream communities. Increased retention of particulate organic matter and production of fine particulate organic matter from decomposing logs alters nutrient fluxes through the biota and subsequently influences the functional response of the fish and invertebrate communities within the stream (Minshall, et al. 1982, Sedell, et al. 1988). In response to changes in organic matter storage, functional responses of invertebrate communities, taxa abundance, and production are reported to vary between erosional and deposit

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depositional habitats, as well as between reaches with and without debris dams (Molles 1982, Smock, et al. 1985, 1989), or logs (Wallace, et al. 1995). In regions with unstable substrates, snags may support a large proportion of the insect biomass and production (Benke, et al. 1984, 1985, Smock, et al. 1985).

In many regions of the United States coarse woody debris was historically a prominent feature in streams, and in some cases log jams stretched for kilometers on both small and larger streams (Swanson, et al. 1976, Triska 1984, Maser and Sedell 1994). Debris removal was originally initiated to provide unobstructed waterways for navigation and transportation of harvested logs. In 1776 the U.S. Congress appropriated money to clear driftwood from streams and rivers to improve navigation, beginning with the Mississippi River. Woody debris removal from rivers remains an active role of the U.S. Army Corps of Engineers (Harmon, et al. 1986), and is one of the primary roles of County Drain Commissioners (locally elected officials charged with creation and maintenance of an extensive network of drainage ditches) in the state of Michigan.

Coarse woody debris abundance in temperate stream ecosystems is regulated by a complex set of factors that act on the source of the wood itself, its delivery to the channel, and lastly, on the myriad of factors that control its retention and mobility once it is delivered to the channel. At regional scales, geomorphic features have regulated the original vegetation of the landscape (Grimm 1984, Host and Pregitzer 1992), as well as the historical and current land use/land cover patterns within the region. Both historic and cu

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and current land management factors in the riparian zone and the floodplain influence the supply of the CWD (Bilby and Ward 1991, Murphy and Koski 1989, Ralph, et al.1994). Forested landscapes are increasingly fragmented by forest harvest as well as land conversion for agricultural production and residential/commercial development. Silvicultural practices alter species composition, number, and size distribution of trees in the upland, and thus modify the potential source and input rates of CWD, particularly in small to medium-sized streams (Bilby 1984, McDade, et al. 1990, Fetherston, et al. 1995). In agricultural and urban areas potential sources of woody debris as well as the stream retention capacity are altered by management practices such as grazing, landscaping, riparian vegetation thinning or removal, dredging and channelization. Although these management activities can undoubtedly reduce the potential supply of in-stream CWD, current riparian vegetation may not accurately reflect standing stocks of CWD. A highly retentive stream channel can contain very old wood (Keller and Tally 1979, Murphy and Koski 1989), which can predate the age of the current riparian vegetation (Swanson and Lienkaemper 1978, Evans, et al. 1993).

The riparian zone and the land-water ecotone mediate inputs of sediment, nutrients, and particulate organic matter to streams, in addition to providing other important ecosystem functions (Gregory, et al. 1991). The primary sources of CWD in streams are derived from natural mortality, fire, disease, insect damage, ice/snow loading, and wind-throw damage to trees in the riparian zone or uplands adjacent to the stream (Keller and Swanson 1979). Processes such as mass soil wasting, bank undercutting and erosion

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erosion, and flooding transport this material into the stream. Beaver may be the primary vector transporting large volumes of CWD to the channel in some systems (Naiman, et al. 1986, Maser and Sedell 1994). Alteration of the hydrologic regime from stream channelization, wetland drainage, or urbanization frequently results in increased bank erosion, one of the primary mechanisms of CWD input to low-gradient streams (Keller and Swanson 1979; Davis and Gregory 1994). Erosion processes are themselves regulated by geologic factors (e.g., soil type, topography), vegetation cover type, and hydrologic regime, in addition to anthropogenic factors including grazing, forest harvest, construction, and agriculture.

Once wood is introduced to the channel it is either retained by obstructions in the channel, or by the channel itself, if the log is large relative to the size of the channel (Keller and Swanson 1979, Keller and Tally 1979). A positive feedback loop is initiated when wood is retained by an obstruction, resulting in debris jams that continue to assimilate wood being transported from upstream. The stability of debris accumulations depends on many factors, most important being the extent of burial, and the magnitude and frequency of flood events (Bilby 1984). Morphological changes in the channel that are attributed to CWD, including plunge pool formation, lateral adjustments, sediment and organic matter retention, can themselves influence CWD mobility and retention. For example, decreased flow velocity due to pool formation will result in decreased stream power and capacity to transport CWD (Braudrick, et al. 1997). Channel bars resulting from sediment and organic matter retention themselves form obstacles for CWD.

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Since CWD fundamentally influences both the structure and function of streams in historically forested regions, identifying the myriad factors that regulate its abundance and distribution is essential for understanding how stream ecosystems are regulated. Many studies have examined the role of coarse woody debris in high- and low-gradient catchments (Table 2-1). However, few studies have attempted to quantify relationships among landscape factors and the observed patterns in CWD abundance and distribution in low gradient systems, particularly in landscapes that are not currently dominated by forests. Stream restoration activities that attempt to increase habitat heterogeneity to enhance fish and invertebrate production frequently use log structures anchored in the channel (Hunter 1991). These structures are subject to failure, and can cause or exacerbate existing problems (Beschta and Platts 1986). The influence of log placement on the channel and the biota has been examined (e.g., Hilderbrand, et al. 1997) but did not account for large-scale factors that influence both the input and retention of CWD in streams. Landscape-scale factors such as land use and surficial geology influence the abundance of woody debris found in stream channels (Ralph, et al. 1994; Richards, et al. 1996) and also undoubtedly play a role in mediating the impact of disturbance events that influence the export of CWD and smaller organic matter fragments. By examining the factors influencing CWD at a range of spatial scales, the extent to which local and regional factors regulate the abundance and distribution of CWD can be discriminated. The goals of this paper are to: 1) characterize the abundance, size, and distribution of CWD in low gradient streams in developed landscapes, and 2) quantify the relative influence of reach- and catchment-scale factors on the abundance and distribution of

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CWD. Parallel examination of the density and distribution of debris accumulations are discussed elsewhere (Johnson 1999*b*) because the factors controlling the formation of debris accumulations are believed to be local in scale.

Methods

Study Area

The Saginaw Bay catchment of Lake Huron encompasses a 16,317 km^2 region, characterized by sand and clay-dominated lowlands rimmed by coarse-textured glacial features such as ground moraines and outwash plains (Figure 1-2; Johnson, et al. 1997). The study region is contained within two major ecoregions as defined by Omernik and Gallant (1986): the Southern Michigan/Northern Indiana Till Plains and the Huron / Erie Lake Plain. Each is subdivided into two sub-regions. Soils in the lake plain are dominated by medium and fine-textured loams ranging to clays, with sand in the outwash plains and channels. These clay regions are extensively drained by artificial drainage and tile systems. The periphery of the basin contains many coarse textured glacial features such as ground moraines and outwash plains. The till plain exhibits the greatest variation in basin topography and contains a high percentage of forested land intermingled with agricultural land and old fields; elevations average about 278 m. The entire drainage was logged for white pine and hemlock between 1840 and 1900 (Quinlan 1997), and forests of the region now consist primarily of second growth hardwood species.

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Previous work (Richards, et al. 1996, 1997, Johnson, et al. 1997) has shown that both land use patterns and Quaternary geology mediate the landscape's response to environmental stress. The sampling design was chosen to reflect these factors. A 2x2 factorial design was used to investigate the influence of underlying geology and land use / land cover on CWD dynamics (Table 2-2; Figure 1-1). Each cell in the design included 3 replicate catchments/streams (n = 12 total), chosen from a pool of candidate catchments. The treatments are designated as: lacustrine / agricultural (Lac/Ag), lacustrine / mixed (Lac/Mix), morainal / agricultural (Mor/Ag) and morainal / mixed (Mor/Mix). Three first to third order reaches in each stream were selected to quantify some internal variation within streams, resulting in a total of 36 subcatchments ranging in size from 712 to 23,448 ha. These sites are collectively referred to as the "core" sites. One site was impounded by beaver during the second year of this study resulting in a total of 35 sites. Longitudinal gradients in streams in a lacustrine agricultural (Lac/Ag) catchment (Bad River, n = 11 including "core" sites), and a catchment dominated by morainal geology and mixed agricultural/forested land use (South Branch Flint River, n = 12 including "core sites) also were examined. These sites are collectively referred to as "longitudinal" sites.

Coarse Woody Debris Abundance, Distribution and Size

Coarse woody debris assessments were performed during low flow conditions during the summer of 1995 (Table 2-3). CWD volume was measured using the line transect method (De Vries 1974, Wallace and Benke 1984). Three random transects a

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across the channel were established in each flow regime (e.g., fast, turbulent; fast, non-turbulent; slow; as per Hawkins, et al. 1993) represented within a 100 m reach. Diameter measurements were obtained for all wood ≥ 0.02 m and 0.25 m in length that intersected the transect and fell within the bank-full channel. Wood volume per unit area was calculated based on the formula:

$$\hat{X}_v = (\pi^2/8L) \sum^{n} d_i^2$$

where L = transect length, and d = stem diameter intercepted by the transect (Wallace and Benke 1984). Volume per unit area was calculated for each transect and summed for each reach. Volume data are reported for size fractions of ≥ 0.02 m diameter and >0.25 m length, ≥ 0.05 m diameter and 0.5 m length, and ≥ 0.10 m diameter and 0.5 m length. The majority of the analyses were performed using ≥ 0.05 m diameter and 0.5 m length data. (Wood density measured by the line-transect method will be referred to throughout as wood volume.)

In addition to volume measurements, counts of the total length of CWD ≥ 0.05 m diameter and ≥ 1 m in length were made at 10 m intervals within the reach and summarized as total meters of wood per m^2 of stream bottom (m / m^2) for each site. (This assessment method is hereafter referred to as the "linear estimation method", and the data generated by this technique will be referred to as 'wood abundance' throughout the text.)

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Debris accumulations were defined broadly to include: vegetation with trapped organic debris, root wads with trapped organic debris, loose accumulations of logs, and log debris dams. Debris accumulations ≥ 1 m^2 in area were counted, mapped, and photographed. Debris accumulations were assigned a size class based on the dimensions of the debris accumulation relative to the channel width at the upstream point of the accumulation location (Table 2-4; Shields and Smith 1992). Debris accumulation data were summarized by total number of debris accumulations per 100 m reach, and a metric reflecting the amount of stream channel covered with debris accumulations, derived from the sum of all debris accumulation sizes per reach (= $\sum$(accum size); Table 2-3).

Channel morphology and habitat structure

At each site, a stream reach of approximately 100 m was sampled. This is usually sufficient to incorporate more than one riffle-pool sequence and represented between 10 - 20 times the stream width (Richards 1982, Bisson and Montgomery 1996). A comprehensive set of parameters commonly evaluated in stream surveys were measured at within each stream reach, representing factors associated with the channel morphology, habitat, and riparian conditions (Table 2-5).

Riparian structure

Measurements and observations of riparian width, riparian slope, vegetative composition and height, riparian and floodplain land use, and floodplain slope were obtained from each bank at three points along the reach (Table 2-6). Riparian zone width, veget

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vegetation height, and slope were encoded separately for the left and right banks, and the six values were averaged to derive a mean value for each site. Riparian zone slope (perpendicular to the channel) was measured directly at six points along the reach using a clinometer. Riparian vegetation height classes (0 = paved, 1 = lawn, 2 = grasses/herbs, 3 = shrubs, 4 = trees) reflected an increasing potential to serve as a source of CWD. Riparian vegetation height values were highly correlated with riparian vegetation cover.

Landscape Structure

Land use, hydrography, Quaternary geology, and elevation databases were used to quantify several aspects of landscape structure (Table 2-7). Catchment boundaries above the sample points were delineated manually and digitized from USGS 1:24,000 topographic maps. Digital elevation data were used to verify boundaries. Hydrography data was derived from digital line graph (DLG) data at a scale of 1:100,000 (USGS). Stream orders (Strahler 1964) and link numbers (Shreve 1966) were assigned as an attribute of the stream data file derived from the USGS as Digital Line Graph files. Mean catchment elevation and slope were derived from 30-second digital elevation models at a scale of 1:100,000. Topography in the region is relatively flat, therefore the standard deviation in elevation was used to represent topographic heterogeneity. Slope was derived from elevation data using ARC/INFO algorithms. Stream density was calculated as the total length of all streams divided by catchment area (km / km^2). All spatial databases were transformed into a common digital format, projected onto a common coordin

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coordinate system (Albers) and analyzed in ARC/INFO as vectors unless otherwise specified.

Land use - land cover data and patch density (a measure of landscape fragmentation; Forman and Godron 1986) reflect the extent of human intervention in shaping the landscape. Land use data for the study area were obtained from the Michigan Department of Natural Resources (Michigan Resource Information System database), based on aerial photography dated in the late 1970's. Mapping resolution for these data is approximately 1 ha, with a minimum lateral dimension of 61 m. Comparison of the digital data with 1987-1988 photographs revealed that the digital data was about 90% accurate over the upper Flint River catchment. The majority of observed land use changes reflected wetland habitat loss near urban centers. The Flint catchment covers a large proportion of the total study area and contains the largest concentration of urban areas, and therefore represents the extreme in land use conversion in the basin, and increases confidence that the land use data reflect conditions during the water quality sampling program. The classification of land use categories was based on a modified version of the Anderson, et al. (1976) scheme, which was constructed specifically for natural resource applications. Based on the areal extent of certain land use classes and previous work (Johnson, et al. 1997; Richards, et al. 1997), land use categories were aggregated into five classes: urban, row crop agriculture, forest, range, and wetlands in most of the analyses. Mixed land use was designated as less than 50% agriculture in the catchment. Agricultural land was highly negatively correlated with both forest and range land, therefore, a derived variable consisting of a ratio of total agriculture: forest + range (AG : FOR + RNG) was substituted for the individual classes. Range lands in this region are predominantly abandoned fields with shrub or herbaceous cover types. Open water was not included as a land cover type in these analyses. Land use values are reported and analyzed as the proportion of total catchment area. Land use patch density was calculated from land use / land cover data as the number of patches per square kilometer.

Quaternary geology data were digitized from Farrand and Bell (1984; Table 2-8), and also were reported as a proportion of the total catchment area. Based on areal extent of minor categories and previous work (Richards, et al. 1996, 1997; Johnson, et al 1997) geological categories were aggregated by particle size or omitted due to the small areas encompassed by that geologic class. Coarse till plus sand and gravel variables were combined because they were highly correlated with one another, and the combined variable enabled us to reduce the total number of geologic variables.

Data Analysis

Distributional properties of all variables were assessed on the raw data and appropriate transformations were applied to non-normal variables. Box-Cox plots were examined to determine the best transformations to achieve normality. Variables not passing the Wilke-Shapiro test for normality were transformed as follows: square root transformations were performed on debris dam abundance and $\sum$(accum size), and log transformations were performed on wood abundance (m / m^2), wood volume (m^3/m^2), wa

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watershed area, and urban and residential land use values by taking the natural log of the datum plus ½ the lowest non-zero values (arcsine transformations were not performed on the land use proportions because of the relatively small range of the data). Pearson correlations were performed for each discrete data set (e.g., landscape, riparian, channel-habitat) to assess the degree of intercorrelation among variables. Highly correlated variables were not included in the analyses, although separate regression analyses were performed to assess the ability of some variables (e.g., urban versus residential and non-residential urban; wetland versus forested and non-forested wetland; coarse till + sand/gravel versus coarse till and outwash sand and gravel) to improve regression models.

The sampling protocol for this study included multiple samples at different locations on the same stream. Samples from adjacent sites on the same river could be spatially autocorrelated, and would therefore not be considered statistically independent. Data from the longitudinal series on the Bad River (n=10) and the South Branch of the Flint River (n=9) were used to calculate Moran's I, a measure of the interdependence between data at adjoining locations (Odland 1988). None of the CWD measures exhibited significant spatial autocorrelation between adjacent sites on either the South Branch of the Flint or the Bad River (Table 2-9). These results were used to justify the assumption that the three sites sampled on each river could be treated as independent samples, and that the longitudinal sites could be grouped with core sites.

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The hypothesis that were tested were:

1. *CWD abundance and distribution are controlled primarily by local factors (e.g., riparian zone structure and composition, channel features).*
2. *Local factors controlling CWD abundance and distribution are themselves controlled by factors at larger spatial scales (e.g., dominant land use, Quaternary geology, topography, landscape fragmentation).*

To test these hypotheses analyses were performed to 1) describe patterns in the distribution of coarse woody debris abundance across the study area, 2) quantify the effects of land use and Quaternary geology on CWD standing stocks, 3) predict CWD standing stock from local, riparian and landscape features, and 4) identify hierarchical relationships among landscape, riparian and local factors influencing the abundance and distribution of CWD in disturbed streams. Analyses were performed using SAS v. 6.1 for Windows and SigmaStat v. 2.03 for Windows unless otherwise specified.

A two-way ANOVA was conducted to determine the effects of land use and Quaternary geology on the number of CWD abundance and volume. To predict abundance (log m / m^2), (sq. rt.) number of debris accumulations / 100 m and (sq. rt.) $\sum$(accum size), multiple regressions were conducted separately with local, riparian and landscape variables. A combined data set, consisting of previously identified predictors at each spatial scale, was used to predict the CWD abundance variables from data at multiple spatial scales. For CWD abundance and volume, regressions were conducted sepa

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separately on morainal and lacustrine sites in an attempt to identify a significant model when none were found for the full data set.

All regression models were examined using the Cp statistic (Draper and Smith, 1981) and R^2 values. Variance inflation factors, and condition indices were examined for the best candidate models to assess the degree of collinearity among independent variables (Belsley, et al. 1980). The candidate models were further examined using partial regression leverage plots, plots of residuals vs independent variables and the Wilkes-Shapiro statistic to examine the assumption of a normal distribution of the residuals. Influential outliers were identified using Cook's Distance (Draper and Smith, 1981). Hierarchical relationships among local and regional factors were inferred by examining the relative strength of the models at each spatial scale.

Since CWD volume based on logs $\geq$ 5 cm was 0 at 19 of 49 sites, regression analyses were not performed; instead, predictions of wood volume ((log) vol $\geq$ 5 cm) were made using a two stage analysis. The first set of procedures was intended to identify predictor variables distinguishing between sites with and without wood $\geq$ 5 cm on the transects (volume = 0 versus volume > 0; hereafter referred to as 'CWD volume presence / absence'). A second analyses, performed only for sites where vol $\geq$ 5 cm was greater than 0 (n = 30), was intended to predict actual CWD volume from three sets of predictor variables.

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A discriminant function was identified to predict CWD volume presence / absence, using a stepwise discriminant function analysis. This procedure selected a subset of predictor variables at each spatial scale which were subsequently used to develop a discriminant criterion to classify each site based on the CWD volume presence / absence, and to estimate the accuracy of the classification. The second stage of the analysis predicted actual CWD volume (>0) using multiple regression, with local, riparian and landscape factors as independent variables, as described above.

Results

Abundance and Size of Coarse Woody Debris Across the Region

In general, coarse woody debris in the study streams was not abundant and the mean size of individual logs was small (Table 2-10). Wood abundance at 10% of sites was zero, and 36% of sites had less than 0.1 m / m^2. Wood volume of logs $\geq$ 0.10 m diameter was 0 at 55% of sites, 0 at 39% of sites when logs $\geq$ 0.05 m diameter were included, and 0 at only 14% of sites when wood $\geq$ 0.02 m diameter was considered. The mean volume of CWD $\geq$ 0.10 m diameter across all sites was 0.0017 $\pm$ 0.0005 m^3 / m^2, and 0.0024 $\pm$ 0.0007 m^3 / m^2 for wood $\geq$ 0.05 m diameter. The mean size of logs across these streams also was small. When wood $\geq$ 0.05 m diameter was considered, mean log diameter was 0.093 $\pm$ 0.007 m and length was 2.5 $\pm$ 0.23 m. Since large wood was rare, a smaller minimum log size was used for this study, despite the fact that this would over-represent the density of wood at these sites, compared with other studies.

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Land Use and Surficial Geology Effects on CWD and Accumulation Abundance

A two-way analysis of variance was performed testing the hypothesis that the abundance and distribution of coarse woody debris differed across sites stratified by dominant land use and Quaternary geology. Significant interactions effects of land use and geology on wood abundance were detected (m / m^2; $p < 0.001$; Table 2-10). CWD abundance was significantly greater in Mor/Mix and Lac/Ag catchments than Mor/Ag and Lac/Mix catchments. Although differences in CWD volume, numbers of logs on the transects, and log sizes were not significant, some strong trends were evident. Mor/Mix and Lac/Ag sites had the largest mean log diameter and length; mean wood volume was large, but highly variable in the Mor/Mix/mixed sites, and was approximately equal in the other three catchment types. Numbers of logs ≥ 5 cm diameter encountered on the transects was greater in morainal than lacustrine sites, but this trend was not apparent for the data set that included small logs (≥ 2 cm diameter; Table 2-10).

A mixed model ANOVA was performed testing LU, GEOL, LU*GEOL treatment effects while accounting for the random effects of the basins. No significant differences resulting from the treatments were observed when variation due to basins was accounted for in the error term of the model. Differences due to error (basin) effects, however, were significant for all CWD measures with the exception of diameter and length. This suggests that either within-basin variation masked the variation due to land use and geology, or there was insufficient power to detect treatment differences due to the reduction in the degrees of freedom from 45 to 10.

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Environmental Factors Influencing CWD Standing Stocks

CWD presence / absence at a site was predicted by a discriminant function consisting of local-scale variables including % open canopy and mean bank-full width. The presence of wood volume > 0 was predicted with an accuracy of 97%, while the sites where wood volume = 0 was predicted with an accuracy of 79%. No significant regression model was found using local-scale variables for predicting the actual volume of CWD at the 30 sites where wood volume > 0 (Table 2-11); however, when lacustrine catchments were examined separately, the percent of slow units in a reach predicted 36% of the variance in woody debris volume. A separate analysis of the morainal catchments did not result in a significant model.

At the intermediate scale a discriminant function consisting of riparian vegetation height and riparian zone width successfully predicted sites where wood volume > 0 with an accuracy of 90%, while sites where wood volume = 0 were predicted successfully only 79% of the time. As with the local-scale variables, no significant regression was found to predict CWD volume from riparian-scale variables, and no significant models were obtained when data were analyses separately for lacustrine and morainal landforms (Table 2-11).

The discriminant function predicting CWD presence / absence consisted entirely of landscape-scale variables included link number, (log) residential urban land, S.D. elevation and the ratio of agricultural to forest + range land. This discriminant function had a

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had an overall prediction rate of 81%; the sites where wood volume > 0 were predicted with a 0% error rate, but sites where wood volume = 0 were very poorly predicted (39% error). In contrast to the local- and riparian-scale variables, a significant model was found to predict CWD volume at the 30 sites with non-zero values. Predictors were: % outwash sand / gravel, % wetland, and % lacustrine clay. An $R^2 = 0.30$ indicates that there is a large amount of variance not accounted for by this model (Table 2-11). Separate analyses for each landform did not improve the predictive power of the model, however, differences in the predictor variables were evident. On lacustrine landforms, outwash sand and gravel and (log) residential urban were identified as predictors, while stream density, the ratio of agriculture to forest land, and coarse tills were significant predictors on morainal landforms. The multi-scale model including both landforms was identical to the landscape model.

CWD abundance (m / m^2) was poorly predicted by local-scale variables, unlike the number of debris accumulations / 100 m and the $\sum$(accum size) metric (Table 2-11). The % open canopy was the only significant predictors of wood abundance. On lacustrine landforms, percent open canopy was a significant predictor of CWD abundance, and explained 36% of the variance, compared to 19% for both landforms combined. No significant models were found for morainal sites. Riparian vegetation height (= riparian vegetation type) predicted both CWD abundance and the presence / absence of wood volume (>0). On morainal landforms, this variable predicted 71% of the total CWD abundance variance when one outlier was eliminated ($p = .0001$). The best lands

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landscape- scale model predicted CWD abundance from link number, (log) urban land, and S.D. elevation. The multi-scale model was identical to the landscape model.

The number of debris accumulations / 100 m was equally well predicted by the local and landscape variables, but was best predicted by the multi-scale model (Table 2-11). The local scale predictors for density of debris accumulations, ∑(accum size), and CWD volume presence/absence were identical: mean bankfull width and percent open canopy. The riparian vegetation height metric was the best predictor of debris accumulation density at the intermediate scale. Link number, (log) residential land use, outwash sand and gravel, and medium till were the best landscape-scale predictors of the number of debris accumulations / 100m. The multi-scale model contained both local and landscape variables including mean bankfull width and (log) residential land use; the R^2 value for this model was 0.61, which was the largest of all of the predictive models based on both landforms.

The metric representing the amount of stream channel covered by debris accumulations, ∑(accum size), behaved similarly to the number of debris accumulations / 100 m, with the exception that the landscape scale model was best predicted by the S.D. elevation, link number, (log) urban land use, and coarse till (Table 2-11). The multi-scale model contained independent variables from each data set: mean bank-full width, riparian vegetation height, and (log) urban land use.

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Discussion

Several local and regional factors account for the patterns in CWD abundance and distribution observed in streams across a disturbed landscape; however, these relationships are complicated by the underlying structure of the landscape and the disturbance history of the region.

Regional patterns in wood abundance and size

Streams of the Saginaw Basin, Michigan contain a lower abundance of coarse woody debris and smaller logs in comparison with forested streams in the United States and elsewhere (see review by Gurnell, et al. 1995). Direct comparison among studies is difficult, however, due to inconsistencies in the minimum size of logs considered, and a lack of studies in similar streams. Previous studies have defined coarse woody debris as logs ranging from 0.05 to 0.20 m in diameter and 1 to 2 m in length. Differences also exist in the use of geometric means versus non-geometric means. Logs with diameters $\geq$ 0.10 m (the most common definition of CWD cited in the literature) are rare in the Michigan streams studied (Figure 2-2). Logs $\geq$ 0.10 m on the wood volume transects were encountered at only 45 % of the sites. A comparison of the density of CWD in developed versus forested landscapes only underscores the scarcity of wood in the Michigan streams (Table 2-12). The volume of CWD observed in this study is comparable to reaches in an agricultural stream in Tennessee that had recently been cleared of CWD (Shields and Smith 1992), to a basin with mixed land use in Hampshire England (Gregory, et al. 1993), and disturbed reaches of some Rocky Mountain streams

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(Richmond and Fausch 1995). In contrast, two low-gradient streams with forested floodplains in Georgia had CWD volumes of 0.0148 and 0.0167 m^3 / m^2 (Wallace and Benke 1984), compared to 0.0007 and 0.0038 m^3 / m^2 in the mixed land use catchments in these Michigan streams. Woody debris standing stocks in the Michigan streams are comparable only to the lowest values reported for old growth forest catchments (summarized by Gurnell, et al. 1995).

Wood volume in these Michigan streams was comparable to the disturbed Rocky Mountain sites, however, the mean log diameter was smaller. Across all of the Michigan sites, the mean CWD diameter (based on diameter $\geq$ 0.05 m) across all sites was 0.093 m, and length was 2.5 m (Table 2-10). Wood diameter at the disturbed sites in the Rocky Mountain study (Richmond and Fausch 1995) ranged from 0.15 to 0.20 m. The low standing stocks of CWD in this study are consistent with the disturbance history of the region, which was logged of native white pine and hemlock from 1840 through 1900, and then subjected to widespread fires followed by extensive soil erosion (Quinlan 1997). While coarse woody debris density is low, the number of debris accumulations / 100 m in this study area is similar to those encountered in some forested streams (Table 2-12). Debris accumulations were defined broadly in this study to include overhanging vegetation and root wads that trapped organic debris (Johnson 1999*b*). The density of debris accumulations consisting only of logs and snags, however, were comparable to a wide variety of stream types including Iowa streams (Zimmer and Bachman 1976 *in* Shields and Smith 1992), an uncleared agricultural stream in Tennessee (Shields and

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Smith 1992), a managed stream with mixed land use in England (Gregory et al. 1993), and a forested stream in New Hampshire (Bilby and Likens 1980). Debris accumulation sizes are difficult to compare across studies due to inconsistencies in measurements methods. The fact that there are large differences in standing stocks of CWD, but similar densities of debris accumulations suggests that the debris accumulations in the Michigan streams are smaller in size and are composed of smaller logs (Johnson 1999*b*).

Aside from disturbance history, differences in CWD abundance among the higher gradient streams, where many studies have taken place, and the lower gradient streams of the Midwest could also be attributed to CWD input mechanisms. Woody debris inputs in high gradient systems are largely due to whole tree or tree-top blowdown, debris slides, debris avalanches, and mass soil movement from adjacent hillsides (e.g., Swanson and Lienkaemper 1978, Lienkaemper and Swanson 1987). Woody debris enters low-gradient streams through blowdown, bank erosion, and ice loading (Keller and Swanson 1979). In this study area many downed trees were observed in the streams resulting from undercut banks and bank erosion. In addition, numerous new limbs and tree fragments were observed in the streams following intense summer storms. In comparison to hillside mass wasting and avalanches which move large volumes of debris into the stream channel in a very short period of time, bank erosion and storm damage deliver smaller amounts of woody debris to the channel. Ice storms such as one that occurred in the northeastern U.S. and Canada in February 1998 have the potential to deliver large quantities of wood over

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Effects of land use and Quaternary geology

The direct effects of land use and landform in these Michigan streams were mixed. Instead, historic forest harvest, along with current land management practices, probably account for the low abundance and the small size of logs in Michigan streams, relative to less disturbed forested systems (e.g., Richmond and Fausch 1995). Land use patterns and landform at the scale of catchments, had a significant effect on CWD abundance (m / m^2) and the number of debris accumulations / 100m (Table 2-10); Mor/Mix and Lac/Ag catchments had a significantly greater abundance of CWD and density of debris accumulations than did Lac/Mix or Mor/Ag catchments. Aside from the treatment differences in land use and Quaternary geology, Mor/Mix and Lac/Ag catchment types differed from the other land use / geology classes by having lower flood heights, steeper catchment gradients with more topographic heterogeneity, and more range and forest land cover (Table 2-13). Lower flood height implies lower stream power and shear stress to transport woody debris out of the reach, while land cover differences point to an absence of agricultural activities (the non-agricultural land use in common across these catchments is range land, as opposed to urban or forested land; Tables 2-14, 2-15). The prevalence of debris accumulations characterized as 'loose log' and 'log/snag' at these sites, rather than 'overhanging vegetation with trapped debris' or 'root wad with trapped debris' (Johnson 1999*b*), suggests that either woody debris that enters the

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channels of these streams is retained due to lower flood heights, or that there is a sufficient supply of CWD upstream or in the riparian zone to replace wood that is transported out of the system.

Other regionally extensive studies of CWD in streams have focused on quantifying the impacts of forest harvest activities and/or identifying associated impacts on stream channel morphology. Extensive stream surveys of this nature have been conducted in western Washington state (Bilby and Ward 1989, 1991, Ralph, et al. 1994, Beechie and Sibley 1997), Oregon (Carlson, et al. 1990), Alaska (Murphy and Koski 1989), the Rocky Mountains in Colorado (Richmond and Fausch 1995), and New Zealand (Evans, et al. 1993). In western Washington, intensive forest harvest did not affect the abundance of CWD, however, basins that had undergone intensive forest harvest had smaller logs that were located near the channel margins. These changes were associated with a decrease in pool area and depth (Ralph et al. 1994). Rocky Mountain streams with past disturbances in the riparian zone (harvested prior to 1900) had less abundant, smaller logs than did streams associated with old-growth forests (Richmond and Fausch 1995). In contrast, Bilby and Ward (1991) documented a rapid (within 5 years of harvest) change in the species mix, a decrease in both CWD abundance and (in streams $\geq$ 10 m wide) average CWD size following harvest. (Bilby and Ward defined CWD as logs $\geq$ 10 cm diameter and 2 m in length.) Variability in streams within a study, as well as larger minimum log length compared to other studies, may partially account for some of the discrepancies in forest impact data.

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Influence of Local-Scale Features

Local-scale factors (especially bank-full width and % open canopy) are better predictors of debris accumulation density and distribution than of CWD density (Table 2-11). Debris accumulation density and distribution are better predicted because debris dam formation requires a physical obstruction such as a downed tree, boulder, point bar or island in the channel. The presence of such obstacles is generally related to the morphology of the channel and the geomorphology of the valley. Logs that are not associated with a debris accumulation (and are not buried) are more likely to be mobilized and transported out of the reach. Wood density measures reflect both the pool of unentrained (mobile) wood as well as that which is entrained in debris accumulations. The abundance of highly mobile wood in the channel, therefore, may bear no relation to local-scale conditions. Bank-full width was positively correlated with debris accumulation density and $\sum$(accum size), and accounted for the majority of the variability in accumulation density and distribution. Gregory and colleagues (1993) explained 19% of the variance in debris accumulation density from the similar features, including distance downstream, and percentages of deciduous and coniferous trees in the reach. Since their catchment lies within one landform, riparian and catchment land use is most likely to exert a relatively greater influence on debris accumulations compared to Saginaw Basin streams.

Harmon, et al. (1986) suggested that the distribution of CWD along a longitudinal gradient is due to a combination of both fluvial and terrestrial factors. In small streams the location of debris accumulations along the longitudinal gradient is regulated by the spatial pattern of log input, since wood is relatively immobile in small channels. In intermediate-sized streams, stable structures such as debris accumulations and boulders entrain CWD in the channel (Swanson and Lienkaemper 1978, Keller and Tally 1979). Channel morphology, including sinuosity, width and depth, and presence of point bars and islands are the most important factors regulating the location of debris accumulations in larger channels (or intermediate channels with smaller CWD). The streams in this study range from 3.6 to 12.6 m wide. Debris accumulations were most frequently found to be associated with the banks, however, other structures which trapped debris included root wads, point bars and islands and snags; many accumulations were not associated with any visible structure in the channel (Johnson 1999*b*). Due to the small average length of CWD in these streams, wood is relatively mobile, compared to other comparable-sized systems. As a result, even in small streams, the mechanisms leading to debris accumulation formation in these Michigan streams are more likely to be similar to those of intermediate or large streams in forested landscapes.

The number and distribution of debris accumulation were well predicted by bank-full width alone; however, only 8% of the variance in wood abundance was explained by bank-full width alone (data not shown), and the relationship between volume (at sites with volume > 0) and bank-full width was not significant. Strong positive relationships between CWD volume and channel width have been found in some studies (Bilby and Likens 1980, Bilby and Ward 1989, Murphy and Koski 1989, Robison and Beschta

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1989), but not others (Ralph, et al. 1994, Richmond and Fausch 1995, Beechie and Sibley (1997). There was no association between number of logs / m and channel width, however, a strong inverse relationship was found when CWD abundance was expressed on an area basis (Beechie and Sibley 1997). Unlike the previously mentioned studies, however, there was no clear relationship between the size of logs and channel width in this study (Table 2-11). Bilby and Ward (1989) predicted 85% of the variance in wood volume, and 79% in wood diameter and length from channel width alone, with CWD volume, diameter and length increasing with channel width. This strong relationship, in contrast to that seen in data in the Saginaw Basin streams, is more than likely due to the fact that their study was located in undisturbed old-growth forest, where streams were within 100 km of one another (and were therefore probably similar in geomorphology and channel form), and had a similar history of discharge patterns. Streams studied by Murphy and Koski (1989) were chosen for their distinct channel, geomorphic, vegetative and hydrologic features, however, all streams were located in undisturbed old growth forests. In contrast, Ralph, et al. (1994) studied catchments in western Washington state that ranged from intensively harvested to pristine, while those studied by Richmond and Fausch (1995) in the Rocky Mountains were either unharvested, or had been harvested around 1900. The Saginaw Basin streams were selected from two contrasting land forms and dominant land use patterns. Furthermore, they have been exposed to numerous large-scale disturbances ranging from forest harvest and fire early late in the 1800's to channelization and other land management practices in modern time. Channel width is largely controlled by catchment area (Richards 1982, Church 1992), however, anthropogenic factors such as stream channelization and land use factors disrupt the natural hydrologic regime and artificially widen and deepen a stream channel. The weak relationships between stream width and CWD size and abundance may be confounded by the combined effects of hydrologic regime and the cumulative effects of land management practices.

In addition to patterns of abundance of debris accumulations along the longitudinal profile of a river, many researchers have reported strong associations between coarse woody debris and plunge pool formation (e.g., Andrus, et al. 1988, Bilby and Ward 1991, Hilderbrand, et al. 1997), lateral adjustment in the channel (e.g., Nakamura and Swanson 1993, Richmond and Fausch 1995), changes in the longitudinal profile of a river (e.g., Beechie and Sibley 1997, Smith, et al. 1993), and channel width (Bilby and Ward 1989; Gregory, et al. 1993). The lack of strong associations between CWD accumulations and channel features in this study is probably due to two interacting factors: logs in these systems are smaller than those encountered in most previous studies of CWD-channel interactions, and these streams have been subjected to a range of management practices that includes debris removal and channelization. Both of these management practices would eliminate any evidence of a structural role for CWD in these streams. In addition, smaller logs are more mobile and are therefore less likely than larger logs to exert control over channel morphology by forming plunge pools and altering channel widths.

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Neither pool frequency nor maximum depth of pools was related to the abundance or distribution of CWD in the Saginaw Basin streams, and correlations between CWD variables and percent of reach with pools or maximum depth of pools were not significant. Only on lacustrine landforms, at sites where volume > 0, was the maximum depth of pools identified as a predictor of wood volume. Along with channel width, the number, location, and volume of pools in a reach have been shown to be very closely tied to the presence of CWD (e.g., Carlson, et al. 1990, Fausch and Northcote 1992, Richmond and Fausch 1995). Beechie and Sibley (1997) noted that pool forming factors in low-gradient streams appear to be formed by mechanisms other than CWD. The history of channelization in this region, and the small average size of the logs in the streams generally preclude CWD from functioning as a pool-forming agent in this region (Johnson 1999*b*). Furthermore, it appears that CWD standing stocks are only partially controlled by the local-scale features measured in this study. The local-scale factors important to CWD abundance (i.e., bank full width, percent open canopy) are themselves influenced by larger-scale factors (Table 2-14).

Influence of Riparian Features

The factors influencing the absence of wood at a site are more difficult to predict than those influencing its presence. The discriminant function predicting the presence / absence of CWD volume (>0) was better able to predict sites with CWD >0 much better than CWD volume = 0. In many areas woody riparian vegetation has been preserved on one ownership block and totally removed on an adjacent parcel (*unpublished*

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observations). Clearly, stewardship practices of individual landowners are important factors controlling the abundance of CWD in streams, and both economic as well as social/ethical issues come into play when a farmer chooses a particular management practice (Ryan, et al. 1999). These issues appear to vary in importance from one landform to the other. For example, a very strong relationship was found between CWD abundance and riparian vegetation on morainal but not on lacustrine landforms. Interestingly, riparian vegetation height is negatively correlated with rowcrop agriculture on morainal but not on lacustrine landforms (Table 2-14). It is likely that social and/or economic issues, (perhaps related to soil productivity) account for the lower variation in riparian vegetation height and riparian zone width on the lacustrine landforms versus morainal landforms. Regardless of the underlying factors governing management decisions, the result is that the riparian vegetation structure of Lac/Ag catchments is more similar to those in the Lac/Mix, compared to the riparian vegetation in the two land use types on morainal landforms.

Riparian vegetation type is more important than riparian zone width when predicting CWD density in Midwestern streams. In addition, the width of the riparian buffer strip is independent of vegetation type (Table 2-14). This relationship is most striking in Mor/Ag catchments, where relatively wide riparian zones coincide with riparian vegetation heights indicative of herbaceous vegetation. The source-distance area for CWD in a stream is less than about 20-30 m (about two tree lengths); therefore, beyond some threshold distance, riparian vegetation does not behave as a source of CWD for

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for the stream (e.g., McDade, et al. 1990). The magnitude of this distance is dependent upon geomorphic factors such as slope, soil type, age and species composition of the riparian vegetation.

Modification of riparian vegetation can rapidly influence the characteristics of the CWD pool in a stream. Bilby and Ward (1991) reported a change in the log sizes as well as the species composition within 5 years of harvest. These disturbance effects are detectable for a very long time, as evidenced by lower wood volumes and log sizes in Rocky Mountain sites with riparian disturbances that occurred around 1900 (Richmond and Fausch 1995). Recovery to preharvest levels is predicted to take more than 250 years in some Alaska streams (Murphy and Koski 1989). Although the effects of past harvest may result in long-term changes in abundance and size distribution, logs may remain resident in the stream for many years and continue to perform ecosystem functions within the channel, unless they are mechanically removed or transported downstream (e.g., Murphy and Koski 1989, Evans, et al. 1993). Riparian vegetation conversion from woody vegetation to herbs and shrubs probably took place in two stages in the Saginaw Basin; during the intensive forest harvest activities late last century, and then again when agricultural production intensified in the region. Unfortunately, the effects of riparian vegetation harvest and conversion are exacerbated by channelization, which, in addition to enlarging the channel, mechanically removes roughness elements such as boulders and logs to enhance drainage from adjacent farm fields. The result is complete removal of all remnant and modern-day CWD from the channel and a functional simplification of the stream channel.

Influence of Landscape Features

Land use and Quaternary geology are integrally linked on this landscape due to the strong interaction between hydrologic processes and soil porosity. Highly impermeable soils associated with lacustrine regions, especially lacustrine clays, are dominated by surface water flows (Wiley, et al. 1997). The resulting "flashy" flow regime may have greater power to transport CWD through the system. In contrast, the more porous soils associated with morainal deposits result in groundwater-dominated systems with relatively more stable flow regimes, which are likely to be more retentive of CWD. The Saginaw basin was historically covered by extensive wetlands, the great majority of which have been drained and are now under agricultural production (Comer, et al. 1993). Within the study area, agricultural production is pervasive but is most intensive in the lacustrine clay regions; wetlands and range land, and to a lesser extent, urban lands, are most prevalent on coarse till or outwash sand and gravel. Forest land cover is found in the floodplains of the larger rivers, and in association with low productivity soils such as lacustrine sands (Table 2-15).

Urban land use, link number, and the S.D. elevation were the best predictors of CWD abundance, debris accumulation density, $\sum$(accum size), and the CWD presence / absence (Table 2-11). In each case, either urban land use or link number explained the gre

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greatest amount of variation in the CWD variables. Link number is most closely associated with catchment size and stream density (Table 2-15), and is also highly correlated with channel morphology, particularly, stream bank-full width, the percentage of the reach with slow units, and the maximum depth of pools (Table 2-14). These relationships are more pronounced on lacustrine landforms, where link number is positively correlated with the presence of outwash sand and gravel lacustrine clay soils, and agricultural crop land. Topographic heterogeneity in this landform is most likely to be associated with the larger river valleys. The association between CWD and link number is reflected through its control on channel morphology. Larger rivers are less likely to have been channelized, and are more likely to be associated with a floodplain (which behaves as a buffer to agricultural land use and urban development). A negative correlation with % open canopy indicates that these systems have woody riparian vegetation that can provide a source of CWD to the channel. Lastly, these lacustrine rivers are characterized by having a deeper pools and a larger percentage of their reach in pool habitat. Such features are known to be associated with the presence of CWD, although the mechanisms forming these pools are independent of the presence of CWD in low gradient streams (Beechie and Sibley 1997).

Urban land use also exhibits some interesting patterns with respect to other landscape variables (Table 2-15). Across the two dominant landforms, urban land use is correlated negatively with agricultural land and positively with range land. Whereas land use x geology interactions were more common on lacustrine landforms with respect to link r

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link number, the interactions with urban land use are most prevalent on morainal landforms. On this landform urban land occurs in association with hilly regions where stream densities are low, soils are dominated by coarse tills, and land use is strongly associated with range, forest and wetland land cover in a catchment. Urban land use influences CWD indirectly through a lack of agricultural land use in the catchment, and more directly through positive correlations with riparian vegetation height (woody vegetation), wider riparian zones, comparatively closed canopies and stable flow regimes. On lacustrine landforms urban land use is highly correlated only with % range land, which has relatively wide riparian buffer strips and a highly variable riparian vegetation structure. Urban land use is primarily associated with residential, rather than commercial development, and is not very abundant across the study region. The median is 5.7% of the catchment on morainal versus 2.7% on lacustrine landforms, which again suggests that the factors such as topographic relief and soil type, in conjunction with land use, are the actual factors controlling CWD volumes in these streams.

The S.D. of elevation variable is common to three of the five CWD models, however, it contributes greatly to the explanatory power of only the $\sum$(accum size) metric. Topographic heterogeneity is not tightly associated with either lacustrine or morainal landforms (Table 2-15). Some moraines with inclusions of outwash are characterized by very low relief, while lacustrine sand dunes have high topographic relief. On lacustrine landforms low topographic relief is chiefly associated with streams characterized by small catchment size, low link number and stream density on lacustrine sand s

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sand soils, with narrow bankfull widths and shallow channels. Land cover is associated with forests and forested wetlands. These characteristics suggest that there is a supply of wood for the channel, along with small channel dimensions that may be relatively more retentive of woody debris. In higher relief areas on lacustrine landforms, the conditions would mirror those described above in conjunction with link number. High topographic relief on morainal landforms is most highly correlated with low stream density, wetland, urban, range and forest land cover, on coarse tills; stable flows and relatively closed canopies would both supply wood and retain it in the channel.

As previously mentioned, the presence of CWD in the stream is more accurately predicted than its absence. Landscape characteristics that account for CWD volume at sites where volume > 0 were different than the landscape variables discussed above. The most important predictors of CWD volume include wetland land cover, outwash sand and gravel and lacustrine clay. Like urban land use, the total acreage of wetlands across the study area is small, never exceeding 13% of a single catchment. There are striking differences between lacustrine and morainal landforms in the median proportion of wetlands, with the median over all lacustrine catchments being 0.3% versus 3.9% in morainal catchments. Wetlands are negatively associated with agricultural crop land, and positively associated with forested lands, which implies a potential supply of CWD in the catchment. A significant correlation also was observed among wetland land cover, riparian vegetation height and riparian zone width, which further suggests that there is a supply of CWD associated with the wider riparian zones in the stream corridor. Lastly, a stable flow regime, indicated by a negative correlation with flood height, suggests that these systems are capable of retaining the CWD that is delivered to the channel. The positive relationship between wetlands and CWD abundance probably stems from both the association with forest land cover and the role of wetlands as a factor moderating peak flows. Lacustrine clays, another predictor of CWD volume, are highly associated with agricultural and use and flashy flow regimes, both of which negatively influence the supply and retention of CWD in streams of this region.

Outwash sand and gravel was an important predictor of both CWD volume and the density of debris accumulations. On morainal catchments outwash sands and gravels are strongly negatively correlated with agricultural land, and positively correlated with range, forest, wetland, and urban land use / covers. The influence of outwash areas on CWD density stems is related to channel morphology (i.e., wide channels, large percent of slow units, presence of deep pools), with wide riparian buffer strips and stable flow regimes. Overall, the absence of agricultural land use and its associated impacts probably accounts for the positive influence of this variable on CWD volume and the density of debris accumulations. On lacustrine landforms, outwash sand and gravels are associated with large river floodplains, areas which are protected from agricultural and urban land uses, and which generally retain woody vegetation in the riparian zone which can contribute CWD to the channel.

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Hierarchical Relationships Among Factors Influencing CWD Standing Stocks

The abundance of CWD in a reach was hypothesized to be controlled by factors operating at local scales, however, local scale factors would be hierarchically controlled by landscape-scale factors. These hypotheses were accepted to be true with respect to CWD abundance and volume. CWD abundance and presence /absence were poorly predicted by local scale factors including percent open canopy in both cases, and open canopy plus bank-full width in the case of CWD presence/absence. The model which combined data from all three spatial scales, did not include either of these two local-scale metrics, but did contain metrics (e.g., link number and to a certain extent, S.D elevation) that are strongly correlated with bank-full width, in particular. As previously stated, this relationship is well recognized in the literature, and lends support to the hypotheses that there is hierarchical control.

These hypotheses are not as well substantiated for the debris accumulation density. First, the local scale model of debris accumulation density accounts for approximately the same amount of variation as did the landscape scale model (Table 2-11), and second, the multi-scale model incorporates both local and landscape variables. Lastly, the predictor variables in the multi-scale model do not reflect the extent of large-scale control over local processes seen in the models predicting abundance and volume. The models predicting the distribution of debris accumulations are reflect both local and landscape-scale controls. The abundance and distribution of debris accumulations in the channel are controlled by within-channel features, as well as the potential supply of CWD from the

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Effects of data type

Wood volume is the measure that is most commonly used for studies of CWD densities in streams. Values derived from the line transect method do not adequately reflect the abundance of wood throughout a reach, and appear to underestimate actual wood volume in the Saginaw streams. In contrast, the line-transect method overestimated wood volume in a lowland Australian river (Gippel, et al. 1996). Wood volume measures that include a set number of logs per reach, or are measured for all logs in a reach may have stronger associations to local and landscape features, however, these techniques are not amenable for use across many sites. The lineal estimation method, which is a more qualitative measure, better reflects the abundance of CWD in a reach. The other two measures of CWD abundance that were well-predicted by the multiple regression models were the number of debris accumulations and $\sum$(accum size). These metrics are easy to perform and are easily reproduced between technicians, and may be viable candidates for other studies of CWD across large numbers of sites.

The low R^2 value of models predicting woody debris volume indicates that either three transects in each habitat type per 100 m reach were not sufficient to capture the variation in wood volume in the reach, or the variables included in the regression analyses did not explain the variation that was present. Another study that measured volu

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volume along a transect (e.g., Wallace and Benke 1984) used fewer transects per length of reach, but sampled longer reaches. Most other studies quantifying wood abundance measured individual pieces of wood throughout the reach, but sampled a restricted number of reaches (e.g., Robison and Beschta 1989, Murphy and Koski 1989, Carlson, et al. 1990, O'Connor 1992). Bilby and Ward (1989, 1991) sampled a large number of stream reaches, but restricted their survey to 50 logs (> 10 cm diameter and 2 m long) at each site. It is impossible to say at this time whether the lack of predictive power for wood volume in this study is due to a sampling issue or to one or more environmental variables that were not measured.

Implications for stream ecology

The most striking outcome of this study and others in these catchments (e.g., Richards, et al.1996, 1997; Johnson, et al. 1997) is the pervasive effect of land form rather than land use on many aspects of the habitat (including woody debris density), community structure, and water chemistry. Agricultural land cover was expected to be associated with lower densities of CWD, while forested land use were expected to be associated with greater densities. Furthermore, local- and riparian-scale factors were expected to play a large role in regulating the overall abundance and distribution of CWD in a stream. Contrary to original expectations, the data indicate that between 40- 50% of the variability in wood abundance (m / m^2) and volume (m^3 / m3) can be accounted for by landscape-scale features (predominantly those associated with the regulation of hydrology and channel dimensions), and less by land use and land cover in the catchment.

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The abundance and distribution of debris accumulations, however, does follow the original expectations by responding to the structural characteristics of the channel and the potential sources of CWD. Most studies of stream ecosystems in highly developed catchments have been designed to characterize the influence of a particular stressor (e.g., forest harvest, agricultural management practices, urban run-off). As a result, many aspects of the structure and function of these ecosystems have not been well documented.

Although debris accumulation density and distributions are well explained by the local, riparian and landscape variables, the relatively low power of both local and landscape characteristics to predict CWD abundance and volume is surprising. These results are probably due to three factors: the first is the lack of direct measurements of hydrologic patterns (e.g., peak flow and duration); streams in this region are largely ungauged, therefore appropriate data describing the hydrograph in the study area were not available. There are currently only three stream gauges in the basin, and these are located in the lower reaches of the basin and therefore do not reflect the intensity and duration of the peak flows associated with the flashy streams of the region. The second factor relates to lack of data regarding the social and economic variables that influence the implementation of management practices, such as the extent and frequency of stream clearing, and the extent of riparian vegetation conversion. The third limitation is related to the complex interactions between land use and Quaternary geology in this region, which are best illustrated by the situation on lacustrine landforms. Catchments dominated by agricultural land uses on lacustrine landforms have among the highest abun

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abundance of CWD and largest number of debris accumulations. However, the proportion of agricultural land use is negatively correlated with CWD abundance over the entire study area. This highlights the role of local conditions in the channel and the riparian zone in lacustrine regions as a controlling factor of CWD density and distribution.

Across the region local-scale factors are important for explaining the distribution of CWD in the reach and the types of debris accumulations that develop (Johnson 1999*b*); the local factor that is the most important predictor, bank-full width, is largely controlled by larger-scale features. Hydrologic regimes are understood to control many aspects of stream ecosystem structure that ultimately regulate the biotic communities (Poff and Ward 1989). The hydrologic regime is itself regulated by catchment climate, topography, geology, soils, and land use. Land use is the most visible of these factors, and has potential to alter many of the physical and chemical attributes of streams ecosystems. As a result, land form is frequently ignored as a controlling factor in studies examining interactions between landscape-scale features and stream ecosystems. The current study serves to illustrate the importance of land form in the hierarchy of factors controlling stream ecosystems, especially in developed catchments.

woody debris effects on streams and stream ecosystems.

Table 2-1. Summary of literature on coarse woody debris effects on streams and stream ecosystems.

FEATURE	LITERATURE REFERENCE
CHANNEL MORPHOLOGY	
influences channel width, depth; alters channel pattern and dimensions	Zimmerman, et al. 1967; Anderson, et al. 1978; Swanson, et al. 1976; Keller and Talley 1979; Keller and Swanson 1979; Triska and Cromack 1980; Bilby 1981; Triska, et al. 1982; Murgatroyd and Ternan 1983; Angermeier and Karr 1984; Bilby 1984; Hicken 1984; Hogan 1986; Andrus, et al. 1988; Bilby and Ward 1989; Robinson and Beschta 1990; Trotter 1990; Spencer, et al. 1990; Nakamura and Swanson 1993; Smith, et al. 1993; Richmond and Fausch 1995; Hilderbrand, et al. 1997.
influences pool-riffle sequence and longitudinal profile	Mosley 1981; Keller and Talley 1979; Bisson et al. 1982; Gregory, et al. 1985; Hogan 1986; Bisson et al. 1987; Andrus et al. 1988; Sedell, et al. 1988; Robinson and Beschta 1990; Nakamura and Swanson 1993; Gregory, et al. 1994; Smith, et al. 1993; Beechie and Sibley 1997; Myers and Swanson 1997.
form plunge pools	Marston 1982; Andrus, et al. 1988; Carlson, et al. 1990; Richmond and Fausch 1995; Beechie and Sibley 1997; Hilderbrand, et al. 1997.
increases channel roughness	Shields and Smith 1992; Trotter 1990.
creates meander cutoffs	Anderson, et al. 1978; Franklin, et al. 1981; Swanson and Lienkaemper 1978, Triska and Cromack 1980.
creates bankside wetland habitat	Triska 1984; Gurnell and Gregory 1987; Andrus, et al. 1988.

Table 2-1 (continued)

FLOW PATTERN / PROCESSES	
increases flow heterogeneity	Zimmerman, et al. 1967; Keller and Tally 1979; Mosley 1981; Angermeier and Karr 1984; Triska 1984; Hogan 1986; Hauer 1989; Robison and Beschta 1990; Shields and Smith 1992.
influences hydraulic retention	Gregory, et al. 1985; Trotter 1990; Ehrman and Lamberti 1992; Raikow, et al. 1995.
influences sediment transport	Beschta 1979; Mosley 1981; MacDonald and Keller 1987; Nakamura and Swanson 1993; Smith, et al. 1993.
increases sediment storage	Beschta 1979; Bilby 1981; Mosley 1981; Likens and Bilby 1982; Bilby and Ward 1989; Potts and Anderson 1990; Malanson and Butler 1990; Nakamura and Swanson 1993
influences bank erosion processes	Keller and Swanson 1979; Murgatroyd and Ternan 1983; Shields and Smith 1992; Smith et al. 1993; Davis and Gregory 1994.
dissipates energy	Keller and Swanson 1979; Davis and Gregory 1994.
influences flood peak timing	Gregory, et al. 1985.
ECOSYSTEM PROPERTIES	
increases invertebrate habitat	Angermeier and Karr 1984; O'Connor 1992.

Table 2-1	(continued)
increases invertebrate production	Benke, et al. 1985; Smock, et al. 1985.
influences invertebrate community composition	Nilson and Larimore 1973; Anderson, et al. 1978; Cummins and Klug 1979; Newbold, et al. 1980; Molles 1982; Angermeier and Karr 1984; Gurtz and Wallace 1984; Wallace and Benke 1984; Benke, et al. 1985; Huryn and Wallace 1987; Ward and Aumen 1987; Smock, et al. 1989; Carlson, et al. 1990; O'Connor 1991; Wallace, et al. 1995; Hilderbrand, et al. 1997.
increases fish habitat	Swanson and Lienkaemper 1978; Gorman and Karr 1978; Anderson, et al. 1978; Keller and Tally 1979; Triska and Cromack 1980; Bisson 1982, Bisson, et al. 1987, 1988; Bryant 1982, 1983; Hortle and Lake 1982; Angermeier and Karr 1984; Murphy, et al. 1986; Sedell, et al. 1988; Fausch and Northcote 1992; Richmond and Fausch 1995; Beechie and Sibley 1997.
provides rearing habitat for salmonids	Hartman 1965; Triska and Cromack 1980; Murphy, et al. 1986; Sedell, et al. 1984; McMahon and Hartman 1989
influences fish community	Angermeier and Karr 1984; Bisson, et al. 1988; Lehtinen, et al. 1997.
provides flow and predation refugium	Bustard and Narver 1975; Triska and Cromack 1980; Tschaplinski and Hartman 1983; Everett and Ruiz 1993.
provides biofilm substrate	Sedell, et al. 1988; Shearer and Webster 1991; Hax and Golladay 1997.
increases organic matter storage	Naiman and Sedell 1979; Keller and Talley 1979; Bilby and Likens 1980; Bilby 1981; Likens and Bilby 1982; Angermeir and Karr 1984; Bilby and Ward 1989; Smock, et al. 1989; Trotter 1990; Jones and Smock 1991; Ehrman and Lamberti 1992; Shields and Smith 1992; Raikow, et al. 1995; Beechie and Sibley 1997.
provides sink for nutrients	Triska and Cromack 1980; Aumen, et al. 1990; O'Connor 1992.

Table 2-2. Distribution of sample catchments and sample reaches (in parentheses) among factor levels in the factorial design. Agricultural lands have a minimum of 60% of land under production.

		Land Use	
		Agriculture	Mixed forest + Agriculture
Geology	Morainal	3 (9)	3 (9)
	Lacustrine	3 (9)	3 (9)

Table 2-3. Coarse woody debris variables measured during the study.

CWD Variable Name	Description	Units
Abundance		
m/m^2	cumulative CWD length per unit area, wood $\geq$ 5 cm diam and 1 m in length	m/m^2
Vol(2cm)	CWD volume per unit area, (wood > 2 cm diameter; .25 m in length)	m^3/m^2
Vol(5cm)	CWD volume per unit area, (wood > 5cm diameter; .5 m in length)	m^3/m^2
Vol(10 cm)	CWD volume per unit area, (wood > 10cm diameter; .5 m in length)	m^3/m^2
Count (2)	# logs counted per transect (wood > 2 cm diameter)	
Count(5)	# logs counted per transect (wood > 5 cm diameter)	
Log Size		
Diam(5)	Mean CWD diameter, wood > 5 cm included	m
Length (05)	Mean CWD length, wood > 0.05 m included	m
Debris Accumulations	(from Johnson !999*b*)	
# Accum	Number of debris accumulations / 100m	
Sum Accum Size	Derived measure reflecting the amount of stream bottom covered by debris accumulations	

Table 2-4. Size classes of debris accumulations based on methods of Shields and Smith (1992). X = channel width at the upstream point of the debris accumulation. The sum of all debris accumulation sizes in each reach represents a measure of the amount of channel covered by debris accumulations.

Size Perpendicular to Flow	Size of Accumulation in Direction Parallel to Flow			
	< 0.25 X	0.25 - 0.5 X	0.5 - X	> X
< 0.25 X	1	2	4	5
0.25 - 0.5 X	2	3	6	7
0.5 - X	4	6	8	9
> X	5	7	9	10

Table 2-5. Channel morphology and physical habitat variables measured during this study. * Indicates the variable was used to predict the abundance and distribution of CWD. Fast and slow units are defined in Hawkins, et al. (1993) and represent riffle and pool habitats.

Variable	Description	Method
Boulders, cobbles, gravel, sand, clay, silt	Proportion of substrate particles in each class	Osborne, et al. 1991; Platts, et al. 1983.
# Fast Units, % Fast Units* (% fast)	Number of fast units per reach and proportion of wetted area with fast units	Hawkins, et al. 1993
# Slow Units, % Slow Units (% slow)*	Number of slow units per reach and proportion of wetted area with slow units	Hawkins, et al. 1993
Maximum depth in fast unit (maxfast)	Greatest depth recorded in the fast units in the reach	Hawkins, et al. 1993
Maximum depth in slow unit* (maxslow)	Greatest depth recorded in the slow units in the reach	Hawkins, et al. 1993
Mean bank-full width* (abankwd)	Mean bank-full width	Osborne, et al. 1991; Platts, et al. 1983.
Mean bank-full depth* (abankdep)	Mean bank-full depth	Osborne, et al. 1991; Platts, et al. 1983.
Wetted Width (width)	Mean width of wetted channel at low flow	Osborne, et al. 1991; Platts, et al. 1983.
Wetted Depth (depth)	Mean depth of wetted channel at low flow	Osborne, et al. 1991; Platts, et al. 1983.
Habitat area (habarea)	Mean width * mean depth	
Habitat volume (habvol)	Mean width* mean depth * reach length	
Flood height* (fldht)	Maximum bank-full depth	
Instream cover amount (incovamt)	Percent of wetted area with cover (e.g., macrophytes, overhanging bank)	Armour, et al. 1983
% Open Canopy Coverage* (canopy)	Proportion of wetted area not shaded by riparian vegetation	Armour, et al. 1983

Table 2
variab

Variab
Width
Slope
Vege
Veg
% R
% F
% V
Flo

Table 2-6. Variables describing riparian zone structure and composition. (* indicates variables used in most analyses.)

Variable	Description
Width* (ripwidth)	width of the covertype immediately adjacent to the river
Slope* (ripslope)	mean slope within riparian zone
Vegetation type (riptype)	vegetation cover type
Vegetation height * (ripht)	vegetation cover type height
% Row crop* (rrowcrop)	percentage of riparian zone with rowcrop agriculture
% Forest (rforest)	percentage of riparian zone with trees and shrubs
% Urban* (rurban)	percentage of riparian zone with urban/residential land use adjacent to stream
Floodplain slope	mean slope within the floodplain.

Table 2-7. Landscape variables used in analyses and spatial data used to derive data. (USFWS = US Fish and Wildlife Service, USGS = US Geological Survey.) (* indicates variables used in most analyses; others are omitted due to high correlations with other landscape variables.)

Landscape Variable	Data Set	Data Source
standard deviation of elevation* (sdelev); mean catchment slope* (slope)	elevation	USGS digital elevation model
proportion of land use classes in catchment; land use patch density (ptchden)	land use / land cover (see text for variables used)	MIRIS database (MI, DNR)
stream density* (strmden)	hydrography; digital elevation model	USGS, digital line graph
proportion of surficial geology in catchment*	Quaternary geology (see Table 2-9 for variables used)	Farrand and Bell 1984
Link number *	Number of first order streams entering above this site	Shreve, 1966
Stream order		Strahler, 1964
catchment area* (log wshed area)	station location; topographic map; digital elevation	GPS readings; field notes; USGS topo

Table 2-8. Aggregation classes for Quaternary geology categories.

Aggregated Class	Quaternary Geology Particle Type
Coarse till	Coarse-textured glacial till, End moraines of coarse-textured till
Medium till*	End moraines of medium-textured till, Medium-textured glacial till
Fine till	End moraines of fine-textured till, Fine-textured glacial till
Sand and gravel*	Glacial outwash sand and gravel and postglacial alluvium; Ice-contact outwash sand and gravel
Clay and silt*	Lacustrine clay and silt
Lac Sand*	Lacustrine sand and gravel, Dune sand
Peat and muck	Peat and muck
Coarse till + sand and gravel*	see text

Table 3.8. Moran's I statistic testing spatial autocorrelation ... the Red River ...

Table 2-9. Moran's I statistic testing spatial autocorrelation among sites on the Bad River. (* Indicates significance at $p = < 0.05$ level with a Bonferroni adjustment).

Distance Bound (km)	5	11	15	21	35	Correlogram
No. Pairs	7	7	7	7	8	Probability
Distance Class	1	2	3	4	5	
(log) m/m2	-0.57	-0.07	0.21	-0.04	-0.15	0.474
(log) Vol	-0.4	0.45*	0.69*	-0.05	0.07	0.170
(log) Diam	-0.09	-0.17	-0.11	-0.22	-0.04	1.000
(log) Length	0.32	-0.07	-0.69*	-0.23	0.02	0.227
# Accum/100m	0.22	-0.27	0.40*	-0.32	-0.59*	0.211

Table 2-10. Mean ± S.E. of coarse woody debris measures across land use (agricultural versus mixed) and Quaternary geology (lacustrine versus morainal) treatments. Wood diameter and length measures are only for sites containing woody debris. Number of sites where a metric is > 0 are also shown. (N = # sites). (*** = significant effect due to LU x Geol; $p < 0.001$).

CWD Measure	Number of Sites > 0	Basin Mean	Lac/Ag (N = 16)	Lac/Mix (N = 9)	Mor/Ag (N = 9)	Mor/Mix (N = 15)
Density						
m / m^2	45	0.25 ± 0.04	0.31 ± 0.08***	0.11 + 0.04	0.09 ± 0.06	0.35 + 0.11***
Vol (≥2cm)	22	0.003 ± 0.0008	0.0020 ± 0.0009	0.0022 ± 0.0009	0.0024 ± 0.0015	0.0050 ± 0.0024
Vol (≥5cm)	30	0.0024 ± 0.0007	0.0018 ± 0.0008	0.0017 ± 0.0008	0.0020 ± 0.0014	0.0038 ± 0.0020
Vol (≥10cm)	42	0.0017 ± 0.0005	0.0015 ± .0008	0.0012 ± .0007	0.0013 ± .0011	0.0024 ± .0012
#/trans (≥2cm)	22	10.5 ± 1.7	7.3 ± 2.1	12.8 ± 4.9	11.2 ± 6.1	12.1 ± 3.0
#/trans (≥5cm)	30	4.2 ± 0.83	2.7 ± 0.8	3.7 ± 1.4	4.9 ± 2.9	5.7 ± 1.7
Log Size		N = 30	N = 9	N = 7	N = 3	N = 11
Diam (≥5cm)		0.093 ± 0.007	0.098 ± 0.015	0.077 ± 0.010	0.081 ± 0.009	0.101 ± 0.011
Length (≥5cm)		2.5 ± 0.23	2.7 ± 0.42	2.2 ± 0.50	2.1 ± 0.29	2.6 ± 0.42

Table 2-10 (continued)

<u>Distribution</u> (from Johnson 1999*b*)

	N = 49	N = 16	N = 9	N = 9	N = 15
#Accums / 100m	6.8 $\pm$ 0.8	6.7 $\pm$ 1.3***	4.9 $\pm$ 1.4	2.0 $\pm$ 0.8	10.5 $\pm$ 1.4***
$\sum$ Accum Size	34.3 $\pm$ 3.8	36.6 $\pm$ 7.3	32.0 $\pm$ 8.1	16.9 $\pm$ 7.3	40.1 $\pm$ 5.9

Table 2-11. Comparison of discriminant functions and multiple regression models based on different spatial scales for coarse woody debris abundance and distribution. (* model applies only to sites where CWD volume was >0; n = 30). Direction of the correlations are indicated next to each independent variable. The best model for each variable is listed in full. Presence/absence refers to CWD volume > 0 (presence) or volume = 0 (absence); see text.

Wood Variable	Local	Riparian	Landscape	Overall Model
Log volume (m^3/m^2) presence/absence, n = 48	Presence/absence: Adj $R^2 = 0.31$; $p = 0.0002$; bank-full width; % open canopy	Presence/absence: Adj $R^2 = 0.46$; $p = 0.0001$; rip. vegetation. ht.; rip. zone width	Presence/absence: Adj $R^2 = 0.45$; $p = 0.0001$; link number; (log) residen. urban; agric : forest + range; S.D. elevation	same as landscape
	Presence/absence = -0.46 + 0.03 (link number) - 0.02 (S.D. elevation) + 0.18 (log residential) - 0.02 (agriculture: forest + range)			

Table 2-11 (continued)

Log volume (m^3/m^2)*: n = 30	Volume*: no significant model [Lacustrine: Adj R^2 = 0.31; p= 0.02; n=15; % slow units] [Morainal: no sig. model]	Volume*: no significant model [Lacustrine: no sig. model] [Morainal: no sig. model]	Volume *: Adj R^2 = .29; p = 0.008 wetland; outwash sand/gravel; lacustrine clay [Lacustrine: no model] [Morainal: no model]	Volume *: same as landscape
	(Log) volume = -5.5 - 0.18 (% wetland) - 0.01 (% lacustrine clay) + 0.02 (% outwash sand/gravel) (n = 30)			
Log m/m2 (n = 47)	Adj R^2 = 0.19; p = 0.002; % open canopy. [Lacustrine: Adj R^2 = .36; p=.001, n =24; % open canopy] [Morainal: no sig. model]	Adj R^2 = 0.37; p = 0.0001; riparian vegetation ht. [Morainal: Adj R^2 = 0.71; p = 0.002, n = 20; riparian vegetation ht.]	Adj R^2 = .42; p = 0.0001; (log) urban; link number; S.D. elevation [Lacustrine: Adj R^2 = 0.46; p = 0.001, n = 24; link number; stream density, (log) urban.] [Morainal: n = 20; no improvement]	same as landscape
	(Log) m/m^2 = - 3.2 + 1.12 (log urban) + 0.08 (link number) + (0.14) S.D. elevation			

Table 2-11. (continued)

(SqRt) # Debris Accum/ 100 m (n = 49)	Adj $R^2 = 0.44$; $p = 0.0001$; bank-full width; % open canopy	$R^2 = 0.36$; $p = 0.0001$; rip. vegetation ht.	Adj $R^2 = 0.48$; $p = 0.0001$; (log) resident. urban; outwash sand / gravel; link number	Adj $R^2 = 0.61$; $p = 0.0001$; (log) resident. urban; bank-full width
	(SqRt) # Accumulations / 100m = - 2.80 + 0.41 ((log) resident. urban) + 2.49 (bankfull width)			
(Sq Rt) $\sum$(Accum Size) (n = 49)	Adj $R^2 = .36$; $p = .0001$ bank-full width; % open canopy	Adj $R^2 = .38$; $p = .0001$ rip. vegetation ht.	Adj $R^2 = .47$; $p = .0001$ link number; (log) urban land use; S.D. elevation; coarse till	Adj $R^2 = .54$; $p = .0001$ mean bank-full width; rip. vegetation ht; (log) urban land use
	(SqRt) $\sum$(accum size) = - 6.5 + 4.4 (mean bankfull width) + 0.85 (rip. vegetation ht.) + 0.65 (urban)			

*Independent variables in the models:
Local: % open canopy, % slow units, flood height, maximum depth in slow units, mean bank-full depth, mean bank-full width.
Riparian: riparian width, riparian zone slope, riparian vegetation height, % riparian zone in rowcrop, % riparian zone in urban, % riparian zone in forest.
Landscape: link number (or log catchment area), mean catchment slope, S.D. catchment elevation, stream density, % agricultural : % forest + % range, % urban (or % residential urban), % wetland (or % forested wetland), % coarse till and % outwash sand/gravel (or % coarse till + outwash sand and gravel), % medium till, % lacustrine sand, % lacustrine clay.
Multi-Scale Model: variables that were significant predictors in the local, riparian and landscape models were used to derive multi-scale models.

Table 2-12. Comparison of large woody debris densities for Saginaw Basin streams in Michigan with published values for other low-gradient or disturbed streams.

Reference	Location	LWD density (m^3/m^2)	Debris Accum /100 m
this study and Johnson 1999*b*	Michigan	($\geq$ 10cm diam): 0.0017 $\pm$ 0.0008 (0 - 0.018); ($\geq$ 5 cm diam): 0.0024 $\pm$ 0.0007 (0 - 0.0313)	6.8 $\pm$ 0.8 (0-22)
Zimmer and Bachman, 1976 *in* Shields and Smith 1992	Iowa streams	-	0.06 - 3.4
Bilby and Likens 1980	New Hampshire	-	14 (2^{nd} order streams) 3 (3^{rd} order streams)
Sedell, unpublished data, *in*: Triska and Cromack 1980.	young growth mixed hardwoods, Michigan	0.008 - 0.016	-
Wallace and Benke 1984	Ogeechee River, GA.	0.0148	-
Wallace and Benke 1984	Black Creek, GA	0.0167	-
Hauer 1989	Meyer's Creek, S.C.	0.011	-
Hauer 1989	Steel Creek, S.C.	0.0002	-
Trotter 1990	New Mexico	-	0 - 10 aspen forest 50 coniferous forest

Table 2-12 (continued).

Shields and Smith 1992	uncleared reach, S. Fk. Albion River, TN	0.043 - .094	3.5 - 5.8
Shields and Smith 1992	cleared reach, S. Fk. Albion River, TN	0.009 - 0.0001	0.6 - 5.8
Gregory, et al. 1993; Gurnell and Gregory 1995	Lymington drainage basin, United Kingdom	0.00006- 0.005 (> 5 cm diam)	0 - 6.1
Richmond and Fausch 1995	disturbed streams; CO	0.0012 - 0.0147	-
Evans, et al. 1993	New Zealand streams		
	old-growth native	1.006 ± 0.107	
	120 year old native	0.712 ± 0.364	
	10 year old native	0.027 ± 0.008	
	10 year old pine	0.020 ± 0.013	
(Gregory and Lienkaemper, unpublished data, *in* Gurnell, et al. 1995	hardwood forest stream, TN	0.0126	-
Beechie and Sibley 1997	Washington State	0.001 - 0.042	-

Table 2-13. Two-sample t-test calculated for selected variables in lacustrine agricultural (Lac/Ag) and morainal mixed (Mor/Mx; Group 1) versus lacustrine mixed (Lac/Mx) and morainal agricultural (Mor/Ag; Group 2) catchments. Bonferroni adjusted probabilities are for pooled variance.

Variable	Group 1 Mean ± S.D.	Group 2 Mean ± S.D.	adjusted p
catchment slope	0.969 ± .969	0.406 ± .211	0.007
S.D. elevation	11.7 ± 5.8	5.9 ± 3.4	0.006
stream density	0.718 ± 0.194	1.00 ± 0.221	0.0004
% range land	14.5 ± 11.5	5.1 ± 2.4	0.04
% sand	8.5 ± 20.6	42.1 ± 46.4	0.03
flood height	1.29 ± 1.04	2.54 ± 1.27	0.008

Table 2-14. Associations between predictors at the local and riparian scale and landscape, riparian and local scale variables across the entire study area (All), and within lacustrine (Lac) and morainal (Mor) landforms. The variables % open canopy, mean bankfull width, riparian vegetation height, and riparian zone width are strong predictors of CWD in the regression models of CWD standing stocks (discussed in the text). Symbols reflect Pearson correlation coefficients. +++ = $p < 0.001$; ++ = $p < 0.01$; + = $p < 0.1$

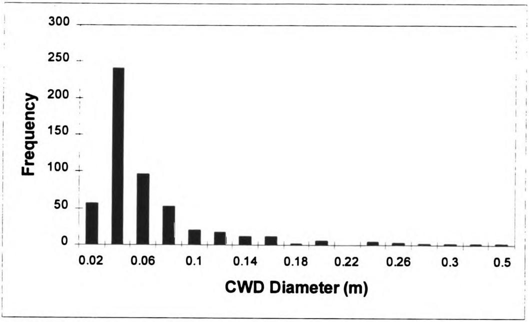
	% Open Canopy			Bankfull Width			Riparian Veg Height			Riparian Zone Width		
	All	Lac	Mor	All	Lac	Mor	All	Lac	Mor	All	Lac	Mor
Catchment Area		-	-	+++	+++	+++			+	+		+
Link Number	-	-		+++	+++	+++			+			+
S.D. Elevation		-	-	++	+++				+			+
Catchment Slope						+				+		+
Stream Density					++							
Coarse Till			-			+			+	+		++
Outwash Sand/Gravel				+	+++	++				++		++
Lacustrine Clay	-			+	++				-			--
Lacustrine Sand				-	--							--
Medium Till	+					-	-	-			--	-
Forest			-		-	++			++			++
Rowcrop			+		++	-	-		-	-		--
Range						+			+			+

Table 2-14 (cont'd)												
Urban	-		-				+		++			+
Wetland		-	-		-	+			++	+		+
Riparian Width						+	+	+	+			
Riparian Veg. Height	--	--	--		+	+				+	+	+
Riparian Rowcrop		+		-		-	--	--	--	-	-	-
% Slow Unit				++	++	+++						+
Max Depth Pool		-		+	++	+				+		+
Bankfull Width		--						+	+			+
Bankfull Depth	-	-			+			+			+	
Flood Height												
% Open Canopy					--		--	--	--			

Table 2-15. Associations between predictors at the landscape scale and landscape, riparian and local scale variables across the entire study area (All), and within lacustrine (Lac) and morainal (Mor) landforms. The variables link number, urban land use, S.D. elevation, and outwash sand and gravel are strong predictors of CWD in the regression models discussed in the text. Symbols reflect Pearson correlation coefficients. n.a. indicates that there is no coarse till associated with lacustrine landforms. +++ = p < 0.001; ++ = p < 0.01; + = p < 0.1.

	Link Number			Urban Land Use			S.D. Elevation			Outwash Sand/Gravel		
	All	Lac	Mor	All	Lac	Mor	All	Lac	Mor	All	Lac	Mor
Catchment Area	+++	+++	+++		-		+++	+++	+	++	+++	+
Link Number				-	-		+++	+++			+++	
S.D. Elevation	+++	+++				+++				++	+++	++
Catchment Slope				+	+	++	++		+++	+++		+++
Stream Density	+	++	+	--		---	+	++	---	--	+	--
%Coarse Till		n.a.		+	n.a.	+++	++	n.a	+++	+++	n.a.	+++
% Outwash Sand/Gravel		+++			-	+	++	+++	--			
% Lacustrine Clay	+++	+++					++	+++		-	+++	-
% Lacustrine Sand	--	---					---	---	-	---	---	--
% Medium Till				-		--			--	-		---
% Forest		-				++		--	+++		--	+++
% Rowcrop	++	+++		---	-	---		++	---	--	+++	---
% Range	-	-		+++	+++	+++	+		+++	+++	-	+++

Table 2-15 (cont'd)												
% Urban	-	-							++		-	+
% Wetland	-	-			-	+++		--	+++		-	++
Riparian Width			+			+	+		+	+++		++
Riparian Veg Height	+			++		++			+			
Riparian Rowcrop					-	-				--		---
% Slow Unit	+++	++	+++	--	--			+		++	++	+
Max Depth Pool	+	+	+		-		+	+		++		+
Bankfull Width	+++	+++	+++				+++	+++		++	+++	++
Bankfull Depth	+									+		--
Flood Height						-			-	--		--
% Open Canopy	-	-		-		-	-		-	-	-	



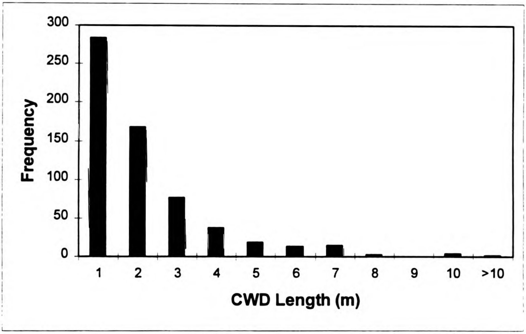


Figure 2-1. Frequency distribution of log diameters and log lengths measured in the Saginaw Basin streams.

Appendix 2-1. Summary statistics of local / channel variables. N = 49.

Local Variable	Median	Mean ± SEM	Range
Flood Height	1.3	1.7 ± 0.18	0.2 -5.2
% fast units	0.72	0.54 ± 0.06	0 - 1.0
% slow units	0.27	0.46 ± 0.061	0- 1.0
Max Depth of Pool	0.6	0.55 ± 0.05	0- 1.2
Mean bank-full width	6.6	7.3 ± 0.4	3.6 - 12.6
Mean bank-full height	0.59	0.65 ± 0.5	0-2
% open canopy	0.70	0.64 ± 0.05	0.02 - 1.0

Appendix 2-2. Characteristics of the riparian zone across 49 sites.

Riparian Zone Variable	Mean	SEM	Range
Width	25.17	1.75	2 - > 40m
Vegetation Ht	5.12	0.54	0.5 - 10m
% Rowcrop	0.32	0.06	0 - 1.0
% Residential Urban	0.21	0.05	0 - 1.0
% Forest	0.00	0.00	0 - .2

Appendix 2-3. Characteristics of catchments in the four landscape treatment groups.

Variable	Lacustrine Agriculture (n=16)	Lacustrine Mixed (n=9)	Morainal Agriculture (n=9)	Morainal Mixed (n=15)
Catchment area (ha)	11,238 ± 2004	2,923 ± 367	8,785 ± 2,129	9,935 ± 1,232
Slope (%)	0.42 ± 0.03	0.32 ± 0.08	0.59 ± 0.02	1.50 ± 0.11
Elevation (m)	217.6 ± 2.6	206.7 ± 3.7	247.9 ± 2.9	307.7 ± 5.44
Patch Density (# / km^2)	6.67 ± 1.86	8.31 ± .33	3.88 ± 0.18	11.7 ± 1.64
StreamDensity (km/km^2)	0.93 ± 0.03	0.77 ± 0.02	1.13 ± 0.07	0.56 ± 0.02
% Agricultural. crop	80.1 ± 3.8	34.9 ± 0.65	81.9 ± 2.8	35.7 ± 2.93
% Forest	11.3 ± 2.1	35.7 ± 6.2	9.3 ± 2.0	22.2 ± 0.85
% Range	3.2 ± 0.7	11.9 ± 4.0	4.7 ± 0.7	22.7 ± 1.26
% Urban	4.1 ± 1.1	9.5 ± 3.4	1.0 ± 0.2	9.50 ± 1.30
% Wetland	0.21 ± 0.04	2.2 ± 0.42	2.2 ± 0.4	5.8 ± 0.48
% Coarse Till	0.0 ± 0.0	0.0 ± 0.0	14.4 ± 3.6	50.9 ± 6.5
% Medium Till	24.1 ± 5.3	7.6 ± 0.4	73.4 ± 6.2	16.0 ± 8.1
% Lacust Sand	21.5 ± 5.8	88.7 ± 5.5	0.0 ± 0.0	0.0 ± 0.0
% Outwash Sand Gravel	5.4 ± 1.6	0.0 ± 0.0	11.7 ± 3.3	29.5 ± 2.8
% Lacust Clay	56.5 ± 4.7	3.7 ± 1.5	0.0 ± 0.0	3.96 ± 2.0

CHAPTER 3

COARSE WOODY DEBRIS ACCUMULATIONS IN LOW GRADIENT STREAMS: RELATIONSHIPS WITH LOCAL AND LANDSCAPE FEATURES

Abstract

The abundance and distribution of four types of debris accumulation were examined across 49 stream reaches in a highly developed region of central Michigan, U.S.A. This study was conducted to characterize the distribution of debris accumulations with respect to land use, Quaternary geology, riparian, and channel-scale features. Coarse woody debris (CWD) standing stocks in these streams are low when compared to forested streams, however, the density of debris accumulations / 100m is similar. This suggests that the debris accumulations in these streams are smaller and contain fewer and smaller logs than streams of forested regions. More stable flow regimes and less extensive channelization are associated with larger densities of 'log / snag' debris accumulation types in the morainal catchments with mixed land use. Active channel management from dredging and removal of riparian vegetation contributes to a small supply of quite mobile CWD in agricultural catchments. As a result, 'loose log' accumulation types are closely tied to bank-full width, which in turn is a function of catchment area. 'Root wad' and 'overhanging vegetation' with trapped debris accumulation types are not well accounted for by landscape- or channel-scale factors. Debris accumulations in these Michigan streams do not play a physical role in modifying channel morphology, as do debris accumulations in forested landscapes. The current study illustrates the importance of land form and flow regime and the secondary role of local-scale conditions in the hierarchy of factors controlling stream ecosystems, especially in catchments impacted by chronic disturbances such as agricultural management practices and channelization.

Introduction

Until the late 1970's coarse woody debris (CWD) in streams was regarded primarily as an obstruction to navigation and fish migration in streams and rivers. Many important ecological functions of coarse woody debris in streams have been identified (see reviews by Harmon, et al. 1986, Sedell, et al. 1988, and Gurnell, et al. 1995). The role of woody debris in streams spans a broad range of physical, chemical, and biological functions that, in turn, regulate many ecosystem properties. Channel dimensions and structures are strongly altered in the presence of CWD, increasing channel width, altering the longitudinal profile of the river, forming plunge pools, and increasing channel roughness (e.g., Zimmerman et al., 1967, Swanson, et al. 1976, Keller and Talley 1979, Bilby and Ward 1989, Nakamura and Swanson 1993). In consequence, flow heterogeneity is increased, along with hydraulic retention, which promotes sediment and organic matter storage (e.g., Gregory, et al. 1985, Ehrman and Lamberti 1992, Nakamura and Swanson 1993). These physical changes in channel morphology, flow regime, and retention dynamics are associated with increases in the amount of suitable habitat, flow refugia, and food for fish and invertebrates (Angermeier and Karr 1984, Benke, et al. 1984, 1985, Bisson, et al. 1982, 1988, Richmond and Fausch 1995, Beechie and Sibley 1997). Despite the wide-spread recognition of the important role of CWD in streams, citizen-based clean-up activities in urban and agricultural areas still remove woody debris from stream channels.

Few studies have attempted to quantify relationships between landscape factors and the observed patterns of CWD abundance and distribution in low gradient systems, particularly in landscapes that have undergone extensive deforestation. Landscape-scale factors, such as land use and Quaternary geology, undoubtedly play a role in mediating the impact of disturbance events (e.g., floods, channelization, forest harvest, alteration of natural riparian communities) that influence the export and retention of CWD and smaller organic matter fragments. Streams in central Michigan have been subjected to a large number of chronic stressors, beginning in the 1840's with forest harvest activities, followed by devastating fires. The denuded landscape was then subject to massive erosion that swept large volumes of sediment into the streams (Quinlan 1997). The current landscape is largely shaped by intensive agricultural practices and residential development. Low-order streams in the Saginaw Basin of Michigan are extensively channelized to enhance agricultural production in low-lying areas that were previously wetlands, leading to reduced substrate and habitat heterogeneity while removing existing pools of CWD. The historic and current land management practices and land use have severely diminished the supply of coarse woody debris, resulting in low standing stocks (Johnson 1999*a*) that are comparable only to disturbed streams in the Rocky Mountains (Richmond and Fausch 1995) and agricultural streams recently cleared of woody debris in Tennessee (Shields and Smith 1992). Under these conditions the dominant structural elements providing in-stream cover, habitat, and organic matter retention consists of overhanging vegetation and root wads of tree stumps or living trees.

Large particulate organic matter and CWD are derived from natural mortality, fire, disease, insect damage, ice/snow loading, and wind-throw damage to trees in the riparian zone or uplands adjacent to the stream (Swanson and Lienkaemper 1978, Keller and Swanson 1979). These materials are transported into streams by mass soil wasting, bank undercutting and erosion, ice and snow damage, and flooding. In some systems beaver may be the primary vector transporting large volumes of CWD to the channel (Naiman, et al. 1986, Maser and Sedell 1994). The processes controlling CWD input to streams are influenced locally by tree species, stand age, soil stability, local topography, and human intervention (e.g., forest harvest and riparian zone clearing), and regionally by geology, climate, valley geomorphology and land use patterns. Once in the channel, CWD mobility and retention is controlled primarily by channel morphology, especially channel width relative to the size of the logs, and other obstructions (e.g., boulders, root masses; Keller and Swanson 1979, Bilby 1984). There exists a complex relationships between those factors influencing the input of CWD to streams on one hand, and those regulating its retention, on the other. Channel morphology regulates CWD retention, yet CWD can have dramatic effects on channel width, pool-riffle sequence (e.g., Keller and Swanson 1979, Gregory, et al. 1985, MacDonald and Keller 1987, McKenney, et al. 1995), suggesting a feedback loop that influences the abundance and distribution of CWD in streams. Debris accumulations are important habitats which support a large proportion of the total taxa richness at a given site (Johnson 1999*d*), however, little is known about these habitats in Midwestern streams. This study was conducted to characterize the distribution of debris accumulations with respect to land use, Quaternary geology, riparian, and channel-scale features. The goals of this chapter are to: 1) quantify and characterize the distribution of four woody debris accumulations types in low gradient streams in developed landscapes; and 2) quantify the relative influence of reach- and landscape-scale factors on the abundance and characteristics of debris accumulations. Debris accumulations are broadly defined here to include log dams and loose log assemblages, as well as overhanging vegetation and root wads that function to trap coarse particulate organic matter, including woody debris.

Methods

Study Area

The Saginaw Bay catchment of Lake Huron encompasses a 16,317 km^2 region, characterized by sand and clay-dominated lowlands rimmed by coarse-textured glacial features such as ground moraines and outwash plains (Figure 1-1; Johnson, et al. 1997). Previous work (Richards, et al. 1996, 1997, Johnson, et al. 1997) has shown that both land use patterns and Quaternary geology mediate the landscape's response to environmental stress, therefore the sampling design was chosen to reflect these factors. A 2x2 factorial design was used to investigate the influence of underlying geology and land use / land cover on CWD dynamics (Table 2-2). Each cell in the design included 3 replicate catchments/streams, chosen from a pool of candidate catchments. Three first to third order reaches within each stream were selected to quantify internal variation within the 12 streams, resulting in a total of 36 subcatchments ranging in size from 712 to 23,448 ha. These sites are collectively referred to as the "core" sites. One site was impounded by beaver during the second year of this study, resulting in a total of 35 "core" sites. Sites along a longitudinal gradient also were examined in a lacustrine agricultural (Lac/Ag) catchment (Bad River, n = 11 including "core" sites), and a catchment dominated by morainal geology and mixed agricultural/forested (Mor/Mx) land use (South Branch Flint River, n = 12 including "core" sites). These sites are collectively referred to as "longitudinal" sites. A total of 49 sites are included in this study.

Coarse Woody Debris Abundance, Distribution and Size

Coarse woody debris assessments were performed at base flow conditions during the summer of 1995. Debris accumulations ≥ 1 m^2 in area were classified by type (Table 3-1; Figure 3-1), counted, mapped, and photographed. The obstacle causing the formation of each debris accumulation also was recorded (e.g., overhanging vegetation, root wad, bank, point bar or island, snag or log, riffle, or no apparent obstacle). Debris accumulations were assigned a size class based on the dimensions of the accumulation relative to the channel width at the upstream point of the accumulation location (Table 3-2; Shields and Smith 1992). Debris accumulation data were summarized by total number of debris accumulations / 100 m reach, median accumulation size, and a metric reflecting the amount of stream channel covered with debris accumulations, derived from the sum of all debris accumulation sizes (Table 3-3) per reach. For statistical analysis of accumulation size x type, nine potential size classes were collapsed into three to reduce

Channel morphology and habitat structure

A stream reach of approximately 100 m was sampled at each site. This was usually sufficient to incorporate more than one riffle-pool sequence and represented between 10 - 20 times the stream width (Richards 1982, Bisson and Montgomery 1996). A comprehensive set of parameters commonly evaluated in stream surveys were measured within each stream reach, representing factors associated with the channel morphology (e.g., bank-full width and depth) and habitat (percent of reach with slow units, maximum depth in slow units (as per Hawkins, et al. 1993), flood height, percent open canopy, percent in-stream cover, substrate composition; Appendix 2-1; Richards et al. 1996, 1997).

Riparian structure

Measurements and observations of riparian width, riparian slope, vegetative composition and height, riparian and floodplain land use, and floodplain slope were obtained at three points along the reach (refer to methods in Johnson 1999*a*). Riparian zone width, vegetation height, and slope were encoded separately for the left and right banks, and the six values were averaged to derive a mean value for each site. Riparian zone slope was measured directly at six points along the reach using a clinometer. Riparian vegetation height values (0 = paved, 1 = mowed lawn, 2 = herbaceous, 3 = shrubs, 4 = trees) reflected an increasing potential to serve as a source of CWD (Appendix 2-2).

shrubs, 4 = trees) reflected an increasing potential to serve as a source of CWD (Appendix 2-2).

Landscape Structure

Land use, hydrography, Quaternary geology, and elevation databases were used to quantify several aspects of landscape structure (methods in Johnson 1999*a*; Johnson, et al. 1997, Richards, et al. 1997). In addition, catchment boundaries above the sample points were delineated manually and digitized from USGS 1:24,000 topographic maps. Digital elevation data were used to verify watershed boundaries. Topography in the region is relatively flat, except in morainal regions; therefore the standard deviation in elevation was used to represent topographic heterogeneity. Stream density was calculated as the total length of all streams divided by catchment area (km/km^2). All spatial databases were transformed into a common digital format, projected onto a common coordinate system (Albers) and analyzed in ARC/INFO as vectors unless otherwise specified. Based on the areal extent of certain land use classes and previous work (Johnson, et al. 1997, Richards, et al. 1997), land use categories were aggregated into five classes: urban, row crop agriculture, forest, range, and wetlands in most of the analyses. Open water was not included as a land cover type in these analyses. Land use and Quaternary geology values are reported and analyzed as proportion of total catchment area (Appendix 2-3).

Data Analysis

Distributional properties of all variables were assessed on raw data and appropriate transformations were applied to non-normal variables. Box-Cox plots were examined to determine the best transformations to achieve normality. Square root transformations were performed on debris accumulation abundances not passing the Wilke-Shapiro test for normality. Pearson correlations were performed for landscape, riparian, channel-habitat to assess the degree of intercorrelation between variables. Highly correlated variables were not included together in the redundancy analyses.

The hypothesis that the number, type, and size of debris accumulations are a primarily controlled by local factors such as channel dimensions was tested. To test this hypotheses analyses were performed to: 1) describe patterns in the distribution of debris accumulation types across the study area, 2) quantify the effects of land use and Quaternary geology on debris accumulation number, size, and type, and the debris attachment point, 3) to identify factors influencing the number, size, and type of debris accumulations, and 4) assess the potential role of CWD debris accumulations as an agent influencing channel features. Analyses were performed using SAS (SAS Institute 1989) and SigmaStat v. 2.03 for windows unless otherwise specified.

To examine the distribution of debris dam types across the study region, a Chi Square analysis was conducted to test the presence / absence across all catchments of individual debris accumulation types, and debris accumulation size x type classes. A two-way ANOVA was conducted to determine the effects of land use and Quaternary geology on the number of debris accumulation types / 100m and the number of accumulation type x size / 100m.

Redundancy analysis (RDA) was used to quantify relationships between the number of accumulation / 100m and environmental variables characterizing local, riparian and landscape conditions (ter Braak 1995), using Canoco v. 4 software (ter Braak and Šmilauer 1998). Redundancy analysis is a direct gradient analysis technique used to detect patterns of variation in the response data set as a function of a predictor or independent data set. RDA selects linear combinations of environmental data that maximize the dispersion of the response data. The pattern of variation in response composition and the relations between independent variables and response variables can be derived from this analysis. Square root transformations were performed on the accumulation type data. A Monte Carlo permutation test was used to determine the statistical validity of the RDA. Tests were conducted by randomly permuting the site numbers in the landscape (or predictor) variables (Johnson, et al. 1997, Richards, et al. 1996). The predictor data were randomly assigned to the response data (debris accumulation type/size) and a new ordination was calculated. This procedure was repeated 200 times to develop a population of eigenvalues. If the debris accumulation type variables respond to the environmental variables, then the test statistic calculated from the observed data will be larger than the data derived from most of the random simulations. An association was considered significant if the observed eigenvalue was within the five largest simulated values ($p < 0.05$).

The interactions between CWD and channel structure are complex. On one hand, in-stream structures trap woody debris and create woody debris accumulations. These accumulations alter flow in the channel, which in turn influences channel width and depth. Many studies have identified strong relationships between channel width and wood abundance and number of debris accumulations (e.g., Zimmerman, et al. 1967, Keller and Swanson 1979, Beschta 1983, Gregory, et al. 1985, MacDonald and Keller 1987, Beechie and Sibley 1997). Regression analyses predicting CWD abundance from channel width in these streams resulted in models with low R^2 values (Johnson 1999*a*). An alternative approach was used here testing the possible effect of channel width on debris dam abundance using a one-way analysis of variance based on channel width, where streams were classified as small (3-6.9 m), medium (7 - 9.9 m) and large ($\geq$ 10 m). In addition, Spearman Rank correlation coefficients between debris accumulation types and bank-full width, bank-full depth, percent slow units, maximum depth of pools, and substrate composition were examined. The association between the maximum depth in pools and the presence / absence of medium- and large-size debris accumulations of all types was examined using a Kruskal-Wallis test. These analyses were conducted on a reduced data set including only sites having debris accumulations ($n = 38$).

Results

Distribution of Debris Accumulation Types

Three hundred and eighteen debris accumulations were counted and characterized across the 49 stream reaches in the study area. There was an average of 6.7 ± 0.8 debris accumulations / 100 m across all sites (Figure 3-2). The median accumulation size was 5.6, exceeding the width of the channel in one dimension (either lateral or perpendicular to flow; see Table 3-2). Sum accumulation size reflects the extent to which the channel is covered with debris accumulations. The range was 0 to 93, and the mean was 33, mirroring the low abundance and numbers of accumulations / 100m. 'Logs/snag' accumulations were the most abundant type encountered (Table 3-4). 'Root wad', 'vegetation', and 'loose log' accumulations were about equally abundant. Medium and large 'log / snag' were the most abundant of the type x size classes of accumulations (Table 3-5). Most 'log / snag' accumulations were associated with the bank (65%), followed by snags (16%; Table 3-6). 'Loose log accumulations generally were not associated with any specific attachment obstacle (61%). 'Vegetation' and 'root wad' accumulations occurred in association with stream banks.

The null hypothesis was that each accumulation type had an equal probability to occur at a site. No significant difference in the presence / absence of debris accumulation types at the sites was found ($p = 0.165$; Table 3-4). The occurrence of the three size classes of accumulations across the reaches also was not significantly different than predicted. However, when the distribution of the four accumulation types classified by three size classes was examined, the resulting type x size classes were not randomly distributed across sites ($p = 0.001$). There were fewer than expected reaches with large 'vegetation', large 'loose logs', large 'root wads' and small 'loose log' accumulation types, and a greater than expected number of reaches with medium 'log / snag' accumulations.

Although they do not constitute debris accumulations, the most prevalent structural element in the stream channel across the 49 sites was overhanging vegetation and root wads without trapped debris. Overhanging vegetation was present at 45% of the sites, and root wads were present at 59% of the sites. At four sites, root wads and overhanging vegetation were the only structural habitat elements in the channel, aside from the sediments. At an additional five sites, the only debris accumulation types present were overhanging vegetation or root wads with trapped debris. Therefore, at 18% of the sites the only apparent habitat structure was in the form of overhanging vegetation or root wads, with or without associated organic debris.

Effects of Land Use and Quaternary Geology

A two-way analysis of variance was performed testing the hypothesis that the distribution of coarse woody debris did not differ across sites stratified by dominant land use and Quaternary geology. Significant differences due to interactions between land use and surficial geology were found in the number of accumulations / 100m ($p < 0.001$; Figure 3-2). There also were significant interaction effects (LU * GEOL) on the abundance of 'loose logs' and 'log / snags' accumulations ($p = 0.01, 0.002$; Figure 3-3). The number of accumulations / 100m as well as 'loose log' and 'log / snag' accumulation types were present in greater abundance in the Lac/Ag and Mor/Mix catchments than in the other two land use/geology treatment categories. Significant main effects were observed on the abundance of the 'vegetation' accumulations types due to land use ($p = 0.006$). The 'vegetation' accumulation type occurred in greater abundance in mixed land use catchments than in agricultural catchments.

Attachment points of the debris accumulation types were also examined with respect to landscape characteristics. A significant interaction effect was seen on 'no attachment point' ($p = 0.04$; Figure 3-4), and a land use effect on 'bank' attachment points ($p = 0.02$). Bank attachment points were more prevalent in mixed than agricultural land use catchments. Debris accumulations with no apparent attachment point were more abundant in Mor/Mix and Lac/Ag than in the Mor/Ag and Lac/Mix catchments.

Landscape and Local Predictors of Debris Accumulation Types

A redundancy analysis (RDA) was conducted to identify the local, riparian, and landscape factors that could account for the distribution of debris accumulation types. All environmental variables combined accounted for 56% of the total variance in the accumulation type data ($p = 0.005$). 'Log / snag' accumulation types and the total number of accumulations / 100 m were best explained by the first RDA axis (Table 3-7), which was positively correlated with stream density, and flood height, and negatively correlated with S.D. elevation, coarse till + outwash sand and gravel, bank full width, catchment size and flood height (Figure 3-5). 'Loose log' accumulations were negatively correlated with % lacustrine sand and positively correlated with bank-full width and catchment area. 'Vegetation' accumulations types were relatively well explained by the inverse of the same variables (Table 3-7). 'Root wad' accumulations were best accounted for by the third axis representing urban land use and a negative association with the percent of slow units in the channel, and bank-full width.

Interaction Between Debris Accumulations and Channel Characteristics

There was no significant difference between density of accumulations in three channel width classes (Figure 3-6a). At bank-full widths between 7 - 9.9 m there were fewer accumulations / 100 than in smaller and larger sized channels. The same results were observed when all debris accumulations were grouped into small, medium, and large size classes (Figure 3-6b). However, a moderate correlation was observed between channel width and the number of medium-sized 'vegetation' accumulations. When only 'log / snag' accumulations were considered (consistent with debris dam types discussed in other studies), medium-sized accumulations increased in number with increasing channel size, and small accumulations decreased with increasing channel size (Figure 3-6c); however, these differences were not statistically significant.

No significant differences in maximum pool depth between sites with and without medium- and large-size debris accumulations of all types were found. Spearman rank correlations between channel and substrate characteristics showed a negative correlation between bank-full width and 'vegetation' accumulation types (r = -0.44). In addition, 'root wad' accumulations were positively correlated with the percent of slow units in the reach (r = -0.46). When similar analyses were performed for streams < 10m wide (n = 28), 'vegetation' accumulations were negatively correlated with bank-full depth (r = -0.56). The strongest correlation between channel characteristics and debris accumulations was for medium 'vegetation' types (r = -0.62). Streams greater than 7m wide (n = 21) exhibited positive correlations between 'vegetation' debris types and the maximum depth of slow units (r = 0.56).

Discussion

Regional patterns in debris accumulation type and size

The most common debris accumulation type in the stream channel across the 49 sites in the study region was the 'log / snag', occurring with a mean abundance of 3.1 accumulations / 100m. Although these accumulation types were abundant across the study region and were found at 25 of the 49 sites, overhanging vegetation and root wads without associated debris were encountered at all but 5 of the 49 sites in the study area. In the absence of other structural elements in the channel, overhanging vegetation and the cavities formed by root wads may be important flow refugia and habitat for the fish and non-burrowing benthic invertebrates in the stream, particularly during high-flow events. The role of bankside vegetation on channel morphogenesis was explored by McKenney and colleagues (1995) in Ozark streams. Depending on the size of the channel and the characteristics of the valley, the function of bankside vegetation varies widely. To my knowledge, no one has quantified the role of this habitat with respect to its potential contribution to secondary production and functional diversity in stream channels with few stable substrates or structural elements.

While the number of accumulations / 100 m may be comparable to those reported in other studies, CWD standing stocks are extremely low and low sizes are small in these streams (Johnson 1999*a*) compared to those reported in the literature. This suggests that the size of debris accumulations in the Saginaw basin are probably smaller than those found in other regions. The density of debris accumulations observed in these Michigan streams is comparable to that observed in an agricultural catchment in Tennessee (Shields and Smith 1992), and streams in Washington State (Sedell, et al. 1988), but are well below those observed for small streams in New Hampshire (Bilby 1979) and Virginia (Smock, et al. 1989; Table 3-8), particularly when only the 'log / snag' accumulation types typically studied are considered. Unfortunately, the size and abundance of debris accumulation are difficult to compare across studies, since standard methods for quantifying debris accumulation size do not exist.

Landscape, riparian, and local influences on debris accumulations

Overall, the low abundance and size of CWD in the Michigan streams is consistent with the fact that the region was completely logged of its native white pine and hemlock from 1840 - 1900, and what little second growth forest persists in this landscape is restricted to fairly small patches on the landscape. Standing stocks of CWD are most greatly influenced by land use and landscape-scale features that regulate channel size and morphology (Johnson 1999*a*). The density and distribution of debris accumulations responds more directly to local-scale features such as bank-full width and percent of open canopy; however, other factors including riparian vegetation type, surficial geology, and land use also appear to influence the density and distribution of debris accumulations.

The interaction between land use and land form had a significant effect on the type of debris accumulations at a site. This interaction was evident from the results of both the analysis of variance and the redundancy analysis of accumulation types (Figures 3.2, 3.5). The abundance of all debris accumulations, especially the 'log / snag' types, were well explained by the entire set of environmental variables, but in particular, by those associated strongly with landforms and topography, (e.g., high S.D. elevation and percentage of coarse till plus outwash sand and gravel, and low stream density and flood heights). This combination of characters is associated with morainal landforms, where the largest number of accumulations / 100 m and the largest standing stocks of CWD were observed, or in the floodplains of the larger rivers on lacustrine landforms (Johnson 1999*a*). Coarse till plus outwash sand and gravel is highly correlated with range land, which is primarily unproductive land, dominated by abandoned farms and old fields (Table 2.15). Riparian zones in the catchments with a large percentage of coarse till or outwash sand and gravel are among the widest in the study area, however, the vegetative composition of those zones is highly variable. With large amounts of CWD and large numbers of accumulations, these results suggest that there is ample source material in the river upstream of the sample sites with non-forested riparian zones, or that the stream is highly retentive of existing CWD. In the South Branch of the Flint River, there is evidence of a great deal of past beaver activity. These sites described above currently have few trees in the riparian zone and many logs appear to be quite old, therefore stable flow regimes associated with morainal landforms appear to be highly retentive of CWD.

In contrast,'loose log' accumulations are more closely associated with catchment area and bank-full width. Catchment area exerts strong control over many aspects of channel morphology, including bank full width and bank full depth (Richards, et al. 1996), suggesting that landscape-scale features have the greatest influence on the abundance of 'loose log' accumulations / 100m. The abundance of 'loose log' accumulations is negatively correlated with the percentage of lacustrine sand, and positively correlated with lacustrine clays, suggesting a strong association with agricultural land uses. Streams in agricultural regions of the study area are the most likely to be channelized. Therefore, loose assemblages of logs in the channel are a natural outcome of the channelization process, since obstacles that would normally trap woody debris have been removed or reduced in number in those streams. Furthermore, flashy flows associated with surface-water dominated flow regimes on lacustrine landforms are likely to mobilize CWD to a greater extent than the flows associated with ground-water dominated systems, such as those in the morainal systems.

‘Vegetation’ accumulations are associated with contrasting environments compared with ‘loose log’ accumulations. In the case of ‘vegetation’ accumulation types, there is a strong positive association with lacustrine sand, which is associated with forested land covers. In addition, there is a weaker association with wetlands. The relationship between ‘log / snag’ and ‘loose log’ accumulation types and environmental variables may be stronger than the vegetation-based types because logs and snags are frequently removed by farmers and the Drain Commission of Michigan, whereas overhanging vegetation is ubiquitously distributed across the study region. Although removal of overhanging willow and alder from the stream banks has been observed, this practice appeared to be less pervasive than debris removal.

Woody debris abundance and size relative to channel dimensions and structure

The pattern of decreasing number and increasing size of accumulations with increasing stream size reported in the literature are contradicted by the results of this study (Figure 3-6). Although a positive relationship between bank-full width and the total abundance of CWD in the channel was observed (Johnson 1999*b*), no significant difference between the number of accumulations / 100 m and channel width was seen when all accumulations were lumped by both size and type (Figure 3-6a), or when accumulations were grouped into small, medium, and large size classes (Figure 3-6b). A trend suggesting an increase in the number of debris accumulations with stream order (Table 3-9) was also observed; however, this trend is opposite that found by Bilby (1979) and Smock and colleagues (1989). Bilby and Ward (1989) and Gregory, et al. (1993)

reported larger numbers of small aggregations in small streams, and fewer large aggregations in larger streams. Bilby (1979) reported 20-40 debris accumulations / 100 m in first order streams, 10-15 in second order streams and 1-6 in third order streams in New Hampshire, and Smock, et al. (1989) reported between 8 and 13 accumulations / 100 m in two first order, low-gradient coastal streams in Virginia (Table 3-8). First order streams in the current study averaged 6.5 accumulations / 100 m (median size = 6.2), second order streams averaged 6.6 (median size = 6.3), and third order streams averaged 9.5 accumulations / 100 m (median size = 5.2; Table 3-9). Since accumulation sizes are based on a proportion of channel width in the current study (Table 3-2), these results may underestimate the size of large accumulations in large streams and overestimate the size of accumulations in smaller streams. (A large accumulation in a small stream may be classified as a small accumulation in a larger stream in the classification system used in the current study.) In a subset of sites in Mor/Mix land use catchments (most resembling forested streams from other studies), a moderate correlation between link number (r= 0.46), mean bank-full width (r = 0.58) and accumulation abundance was observed. This correlation did not hold for Lac/Ag catchments, which contained the second largest CWD standing stocks and numbers of accumulations. These results suggest that underlying factors not associated with wood supply are effecting some control over the abundance of CWD and accumulations in this region. The major difference between the two catchment types lies in the degree to which groundwater dominates flow.

There are at least two possible explanations for the reversed trend in the number of accumulations relative to stream size observed in the Michigan streams. First, many first and second order streams have been channelized and cleared by the County Drain Commission Office. Historic data to determine whether and when the streams had been channelized are lacking. To address this issue 49 stream reaches were examined with the assumption that channelized streams would have smaller channel width:depth ratios than unchannelized streams. The width:depth ratio was significantly larger in Mor/Mix catchments than the other land use / geology types in the study area. The streams that did not appear to have undergone extensive channelization were also more likely to resemble forested streams examined in other studies. In the Mor/Mix streams, no significant correlation was seen between the number of accumulations and stream order ($r = 0.21$) and bank-full depth ($r = -0.11$), and only moderate correlations with link number ($r= 0.46$) and mean bank-full width ($r = 0.58$).

A second explanation for the pattern in accumulation number with respect to channel size is that headwater streams have narrower floodplains, causing them to be more vulnerable to development than the downstream reaches with extensive floodplains. This would alter the availability of source material in the headwater relative to the larger reaches. In all probability, however, the real explanation for the reversed trend in the number of accumulations with channel size is probably a combination of the two factors: land use patterns in the headwaters, along with active debris clearing.

CWD accumulations in these Michigan streams do not appear to influence channel morphology to the extent seen in forested streams. The lack of strong associations between CWD accumulations and channel features is probably due to three interacting factors: 1) logs in these systems are smaller than those encountered in most previous studies of CWD-channel interactions, 2) these streams have been subjected to a range of management practices that includes debris removal and channelization, and 3) flashy flow regimes on lacustrine land forms rapidly transport wood out of the reach. Many researchers have reported strong associations between coarse woody debris and plunge pool formation (e.g., Andrus, et al. 1988, Bilby and Ward 1991, Hilderbrand, et al. 1997), lateral adjustment in the channel (e.g., Nakamura and Swanson 1993, Richmond and Fausch 1995), and changes in the longitudinal profile of a river (e.g., Beechie and Sibley 1997, Smith, et al. 1993). In low gradient streams, however, the mechanisms related to pool formation are thought to be related more to valley geomorphology than to the presence of CWD (Beechie and Sibley 1997). Aside from potential geomorphic factors, smaller logs are more mobile, therefore, they are less likely than larger logs to exert control over channel morphology by forming plunge pools and altering channel widths in this study area.

The spatial distribution and structure of debris accumulations in small streams reflects the input mechanisms for that region, as well as channel shape and dimensions. Debris in small streams rarely moves except perhaps under large flow events. Wood mobility is constrained by the size of the log relative to the channel dimensions (Bilby

1984, Bryant 1983), log orientation and geometry (e.g., presence of branches; Bilby 1984), extent of burial (Bilby 1984), presence of obstructions in the channel, and flow conditions. In intermediate streams debris accumulations tend to form behind boulders, large pieces of CWD, and other stable structures in the channel (Keller and Swanson 1979; Keller and Tally 1979). In larger streams, debris accumulations form at stream confluences, at upstream point of islands and point bars, and in depositional zones of the channel (Harmon, et al. 1986, Abbe and Montgomery 1997). Since logs in the Michigan streams are small relative to the size of the stream channels, they are readily mobilized, resulting in a distribution pattern similar to larger streams (e.g., Keller and Swanson 1979).

Retention structure and dynamics vary with channel dimensions. In these Michigan streams, the most retentive structure in the channel was associated with the bank or stream margin. This is not surprising, given the types of the debris accumulations studied, (e.g., root wads and overhanging vegetation with trapped debris, in addition to log dams). However, woody debris in 'log / snag' accumulations in the current study was most frequently associated with the bank, followed by vegetation (root wads, snags, and overhanging vegetation). 'Loose log' accumulations were seldom associated with a particular obstruction. Debris dams were the largest retention devices for dowel rods in a 3rd order, low gradient woodland stream, followed by single CWD pieces and roots (Ehrman and Lamberti 1992). However, dowel rods are much smaller than the CWD considered in most woody debris studies, and time frames for the experimental releases were in the order of minutes to hours. In a first order low gradient stream, Smock and colleagues (1989) reported that 52% of the debris dams were associated with root masses. In higher-gradient streams in the Rocky Mountains (Richmond and Fausch 1995), and larger low-gradient streams in Alaska and Washington state (e.g., Bilby and Ward 1989; Robison and Beschta, 1989) woody debris was frequently associated with the stream margin. Wood is more readily mobilized and redistributed by fluvial processes in larger streams. These results highlight the effect of the simplified channel morphology in these streams with respect to the process of debris dam formation. Stream channelization removes structures such as point bars and islands, resulting in a pool of highly mobile CWD.

Many debris accumulations in these Michigan streams were not associated with a specific retention structure ('no apparent' obstacle). The lack of structural heterogeneity in many of these streams and the prevalence of debris accumulations not associated with a specific retention structure probably account for the large pool of CWD that remains mobile (Johnson 1999*c)*. Therefore, the function of CWD as flow refugia, retention structures for small particulate organic matter, and a habitat component of the stream ecosystem may be limited in these Michigan streams. The prevalence of loose logs and accumulations that were not associated with a visible retention structure not unexpected. Debris accumulation surveys were conducted during base flow conditions. When discharge decreases, particulate organic matter drops out of the water column and larger pieces in the channel form obstacles for other material moving downstream. These particles are among the first to be mobilized when discharge increases (Braudrick, et al 1997). Abbe and Montgomery (1996) classified debris dam types based on their relative location in the channel. In their system, bar top jams were the most similar to the definition of 'loose log' accumulations used in the current study. Bar apex jams formed barriers to flow and thus potentially had a large influence on channel morphology. Meander jams were deposited at the upstream head of a point bar and functioned to armor the banks. These types were rare in the Michigan streams for reasons that relate both to land form and land use patterns in the basin.

Conclusions

The Saginaw Basin streams in this study contained very low standing stocks of CWD compared to those reported from less disturbed streams (Johnson 1999*a*). Interestingly, the number of debris accumulations / 100m was comparable to values reported for other regions with much higher standing stocks of CWD. This suggests that the debris accumulations in the Michigan streams are smaller, and entrap fewer and smaller logs than in other streams. A safe, standardized method for measuring the size of debris accumulations is needed to verify this assertion.

The size and abundance of debris accumulations in these highly disturbed streams do not follow the same pattern of decreased abundance and increasing size with increasing channel size, nor do they play a physical role in modifying channel morphology, as do debris accumulations in forested landscapes (e.g., Andrus, et al. 1988, Bilby and Ward 1989, Bilby and Ward 1991, Nakamura and Swanson 1993, Richmond and Fausch 1995, Gregory, et al. 1993, Smith, et al. 1993, Beechie and Sibley 1997, Hilderbrand, et al. 1997). Streams in Mor/Mix land forms, however, display trends that are more similar to those reported in the literature, with moderate correlations between debris accumulation abundance and channel width.

Active channel management from dredging and removal of riparian vegetation in the agricultural catchments contributes to a poor supply of CWD, in conjunction with few in-stream obstacles to retain logs in the channel. Stable flows and less channelization positively influence the standing stocks and number of accumulations in the morianal catchments with mixed land use. Thus, both land form and the association of land use practices with those land forms, influence the abundance and distribution of CWD in these highly impacted streams. Land form is frequently ignored as a controlling factor in studies examining interactions between landscape-scale features and stream ecosystems. The current study illustrates the importance of land form and flow regime in the hierarchy of factors controlling stream ecosystems, especially in catchments impacted by chronic disturbances such as agricultural management practices and channelization. While bank-full width was moderately associated with 'loose log' and 'log / snag' accumulations, catchment area plays a strong role in controlling channel dimensions (Richards 1982). The combined presence of landscape and local variable in the statistical analyses probably overshadows the effects of channel-scale features reported in the literature. Clearly management activities such as channelization and agricultural production, combined with the historic harvest have had a long-lasting effect on the input and retention of CWD in these streams. Factors that appear to influence the abundance and distribution of four different debris accumulation types have been identified, however, further studies to examine the role of these accumulations in low-gradient, highly developed catchments are warranted, since little is known about their relative importance with respect to fish and macroinvertebrate community structure and productivity.

Table 3-1. Description of debris accumulation types, aggregated classes, and attachment points of debris accumulations in the channel. All accumulation are greater than 1 m^2 in area. Aggregated types were used to assess the combination of size and type of debris accumulations. (Variable name in parenthesis.)

Debris Accumulation Type	Description	Aggregated types	Attachment Points
Vegetation w/ trapped debris (vegetation)	Overhanging vegetation with trapped organic matter (size of twigs or larger)	Vegetation w/ trapped debris = 'Vegetation'	Bank
Root wad w/ trapped debris (root wad)	Root wads on bank with trapped organic matter (size of twigs or larger)	Root wad w/ trapped debris = 'Root Wad'	Point Bar or Island
Logs on point bar, island, bank, channel (log dam)	Logs greater than 5 cm diameter in an aggregation. This category is aggregated from 3 separate categories based on location (e.g., bank, channel, or point bar).	Logs and snags = 'Log / snag'	Downed tree/Snag
Snag (snag)	Downed tree, with or without an associated debris dam	Logs and snags	Overhanging vegetation, including root wads
Logs loosely aggregated (loose logs)	Logs greater than 5 cm diameter in a loose aggregation	Loose Logs = 'Loose log'	No apparent attachment point

Table 3-2. Size classes of debris accumulations based on methods of Shields and Smith (1992). X = channel width at the upstream point of the debris accumulation. Classes 1-3 were aggregated to form the size category = small; classes 4-7 = medium; classes 8-10 = large. The sum of all debris accumulation sizes in each reach represents a measure of the amount of channel covered by debris accumulations.

<table>
<tr><th rowspan="2">Size Perpendicular to Flow</th><th colspan="6">Size of Accumulation in Direction Parallel to Flow</th></tr>
<tr><th colspan="2"><.25 X</th><th>.25-.5X</th><th colspan="2">.5-X</th><th>>X</th></tr>
<tr><td><.25X</td><td>1</td><td rowspan="2">SMALL</td><td>2</td><td>4</td><td rowspan="2">MEDIU M</td><td>5</td></tr>
<tr><td>.25-.5X</td><td>2</td><td>3</td><td>6</td><td>7</td></tr>
<tr><td>.5-X</td><td>4</td><td rowspan="2">MEDIU M</td><td>6</td><td>8</td><td rowspan="2">LARGE</td><td>9</td></tr>
<tr><td>>X</td><td>5</td><td>7</td><td>9</td><td>10</td></tr>
</table>

Table 3-3. Coarse woody debris accumulation abundance and size variables measured during the study.

CWD Variable Name	Description
# Accum	Number of debris accumulations per 100 m
Median Accum Size	Median value of debris accumulation size classes per reach
Sum Accum Size	The amount of stream bottom covered by debris accumulations, derived from the sum of all accumulation sizes in a reach.

Table 3-4. Summary of debris accumulation types across 49 stream reaches.

Debris Accumulation Type	Number of Sites	Total Number of Accumulations	Mean per Site	S.E.M	Range
Log / snag	25	147	3.1	0.51	0-13
Root Wad w/ Debris	13	60	1.2	0.24	0-8
Loose Log	12	57	1.2	0.31	0-12
Vegetation w/ Debris	19	54	1.3	0.30	0-4

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Table 3-6. Summary of debris accumulation attachment locations for each accumulation type. Missing data indicate categories that were not likely to occur due to the character of the debris accumulation type.

Debris Accumulation Attachment Point	Vegetation w/ debris/ 100m	Root Wad w/ debris/ 100m	Loose Logs/ 100m	Log / snag/ 100m
Bank	52 (96%)	59 (98%)	8 (14%)	96 (65%)
Point Bar/ Island	2 (4%)	0 (0%)	4 (7%)	14 (9%)
Snag	-	1 (2%)	1 (2%)	23 (16%)
Vegetation	-	-	7 (5%)	6 (4%)
Riffle	-	-	2 (3%)	0 (0%)
No Apparent	-	-	35 (61%)	8 (5%)

Table 3-7. Results of redundancy analysis; fit as a fraction of the variance of woody debris variables.

Wood Variable	RDA 1[1]	RDA2[2]	RDA3[3]	Total Variance Explained (%) (all axes)
Log / snag	**0.54**	0.01	0.04	66.1
# Accum/ 100m	0.60	0.03	0.01	63.8
Loose Log	0.11	**0.36**	0.00	53.1
RootWad	**0.50**	0.07	**0.38**	51.3
Vegetation	0.00	.24	0.12	44.2

[1] RDA Axis 1 is positively correlated with stream density and flood height and negatively correlated with S.D. elevation, coarse till + outwash sand and gravel, mean bank-full width, catchment area, and flood height.
[2] RDA Axis 2 is positively correlated with mean bank-full width and catchment area, and negatively correlated with lacustrine sand.
[3] RDA Axis 3 is positively correlated with urban land use and negatively correlated with % slow units in the reach.

Table 3-8. Comparison of large woody debris densities for Saginaw Basin streams in Michigan with published values for other low-gradient or disturbed streams.

Debris Accumulations / 100 m	Location	Reference
6.7 $\pm$ 0.8 (0-13)	central Michigan (49 stream reaches)	this study
0.06 - 3.4	Iowa streams	Zimmer and Bachman, 1976 (*in* Shields and Smith 1992)
2-8	Washington	Sedell et al. 1988
3.5 - 5.8	uncleared reach, S. Fk. Albion River, TN	Shields and Smith 1992
0.6 - 5.8	cleared reach, S. Fk. Albion River, TN	Shields and Smith 1992
0 - 2.4	Lymington drainage basin, United Kingdom	Gurnell and Gregory 1995
0-10	aspen forest, New Mexico	Trotter 1990
8-13	1^{st} order stream, Virginia	Smock et al. 1989
20-40	1^{st} order stream, New Hampshire	Bilby 1979
10-15	2^{nd} order stream	Bilby 1979
1-6	3^{rd} order stream	Bilby 1979

Table 3-9. Summary of the mean number of debris accumulation and median size by stream order and channel width. (Streams without debris dams are excluded from this analysis; n = 39.)

Stream order (n)	mean # debris accum / 100 m	median size	size range
1 (2)	6.5 ± 2.5	6.2	5.5 - 7
2 (14)	6.6 ± 1.4	6.3	4 - 9
3 (21)	9.5 ± 0.92	5.2	2.5 - 8
4 (1)	13	5.0	5

A.
B.
C.
D.

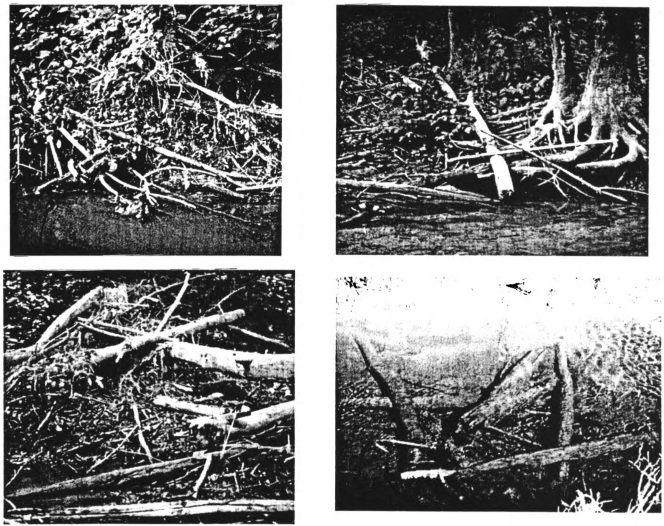


Figure 3-1. Examples of four debris accumulation types. A) Vegetation plus trapped debris, B) Root wad with trapped debris, C) Log/snag, D) Loose logs.

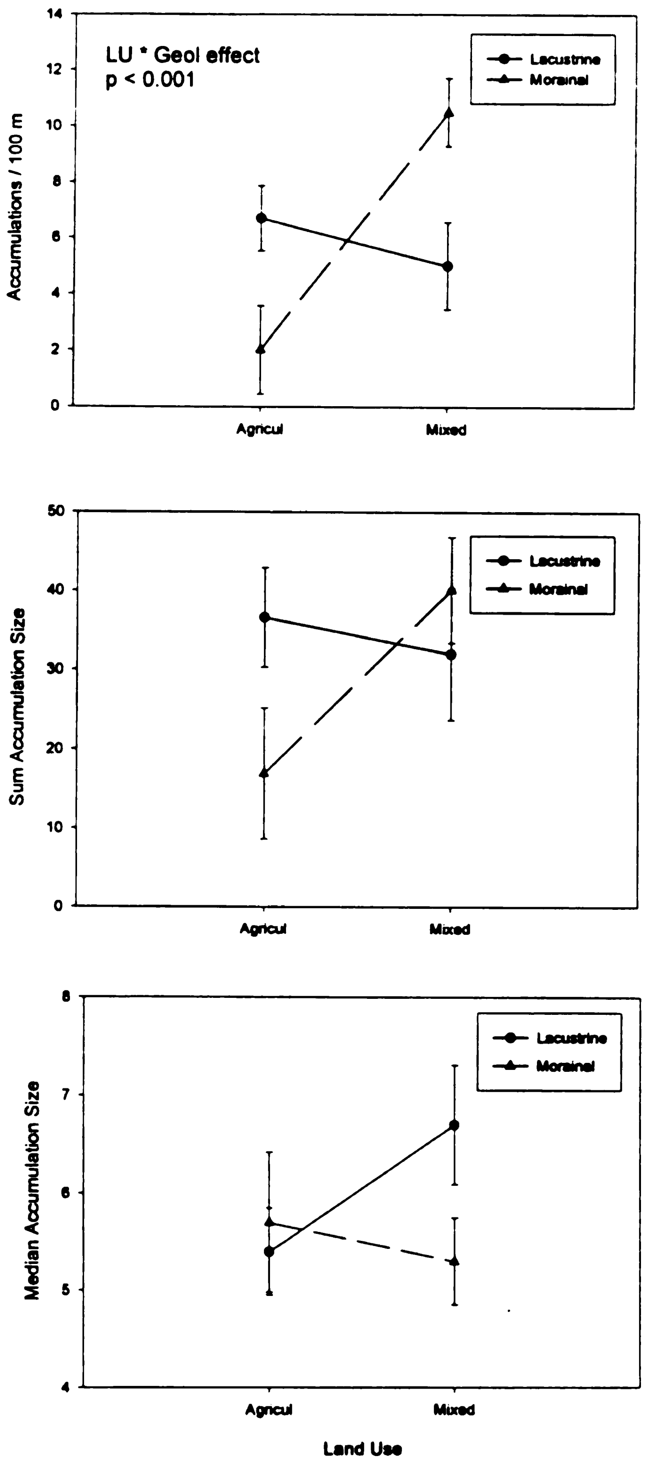


Figure 3-2. Mean and S.E. of # debris accumulation/ 100m, debris accumulation size, and the sum of the accumulation sizes (see text) across land use and geology treatments. Results of two-way ANOVA are indicated.

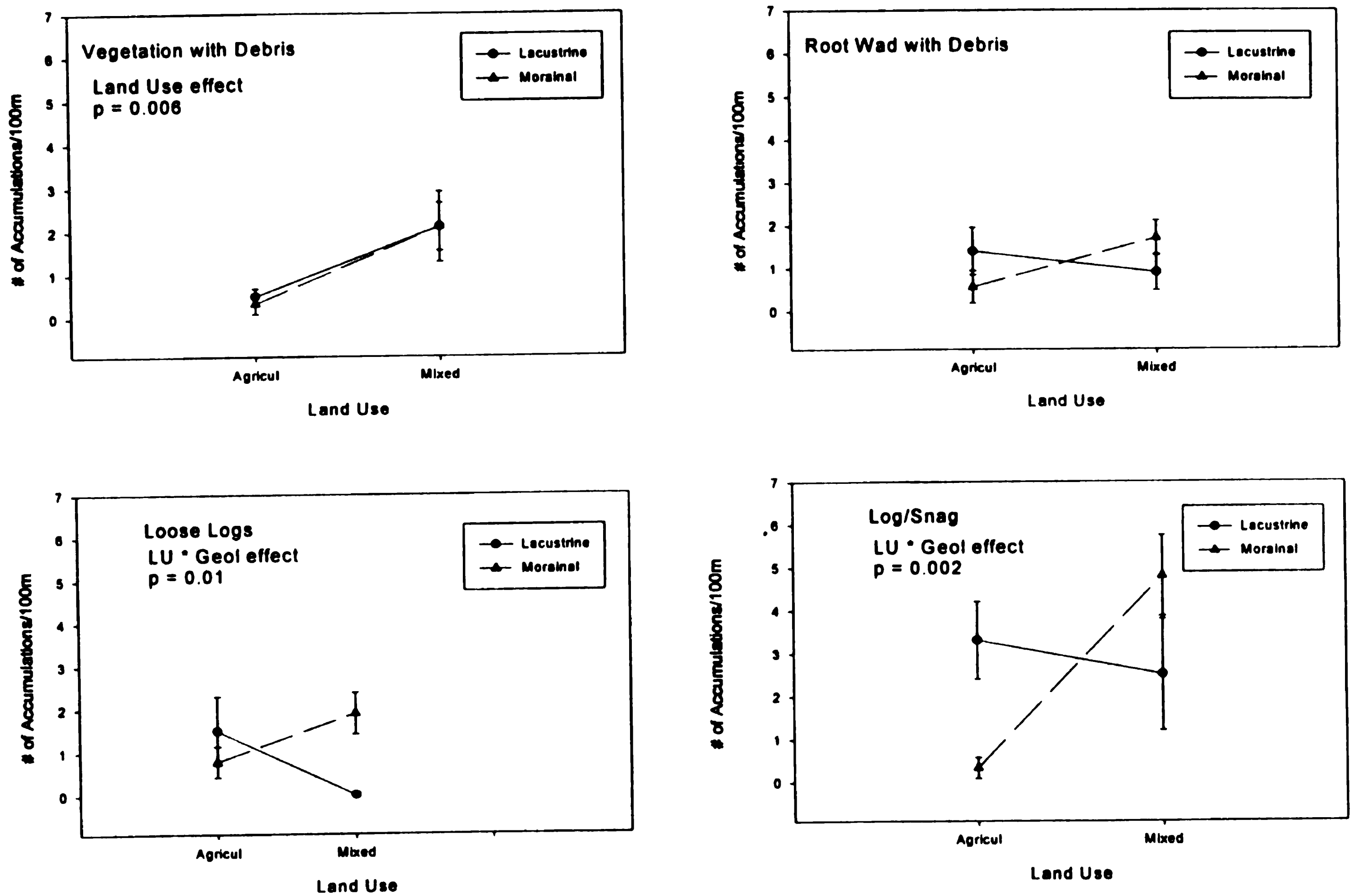


Figure 3-3. Mean and S.E. of # debris accumulations /100m of four accumulation types across land use and geology treatments. Results of two-way ANOVA are indicated.

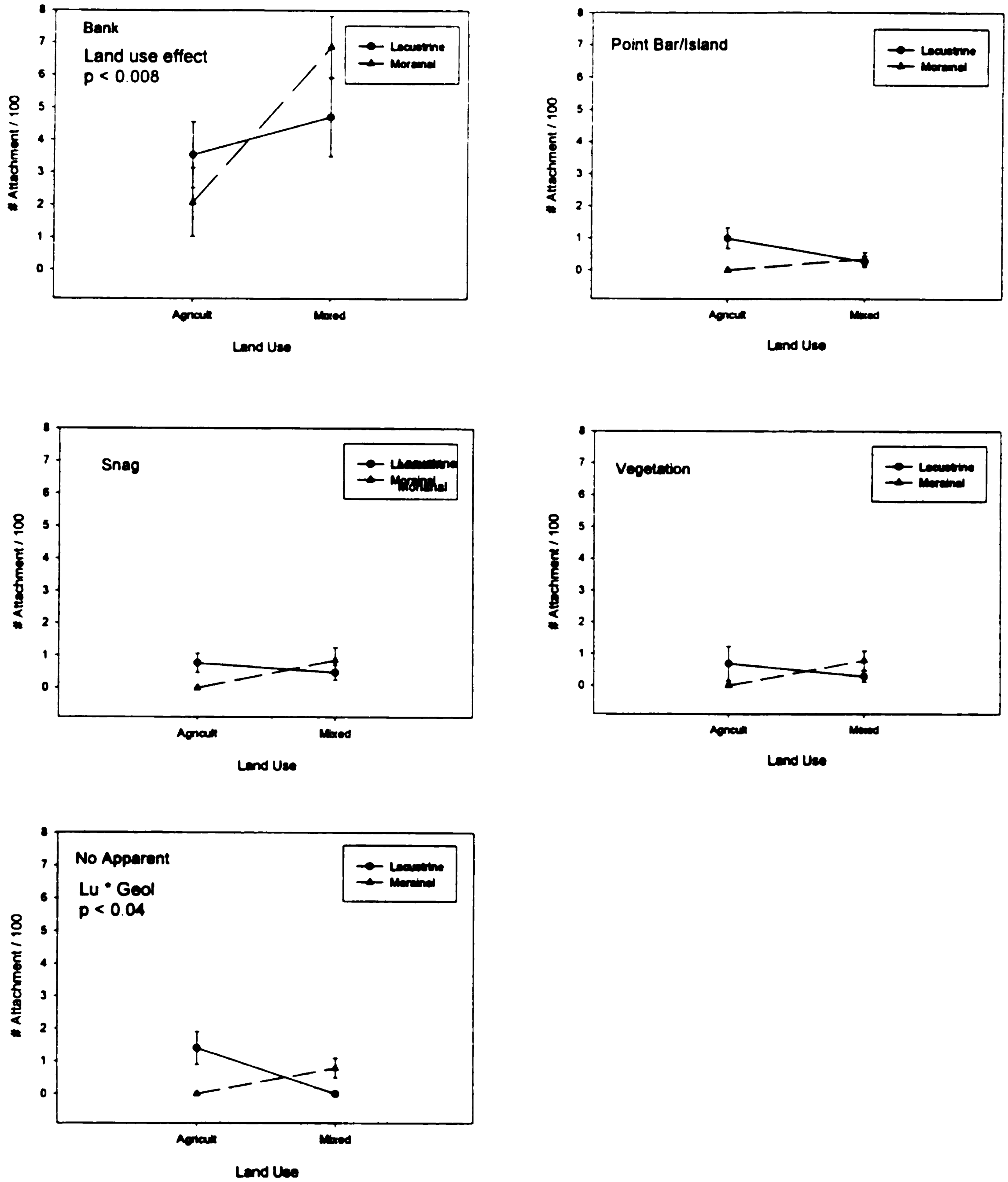


Figure 3-4. Mean and S.E. of # debris accumulation attachment locations /100m across land use and geology treatments. Results of two-way ANOVA are indicated.

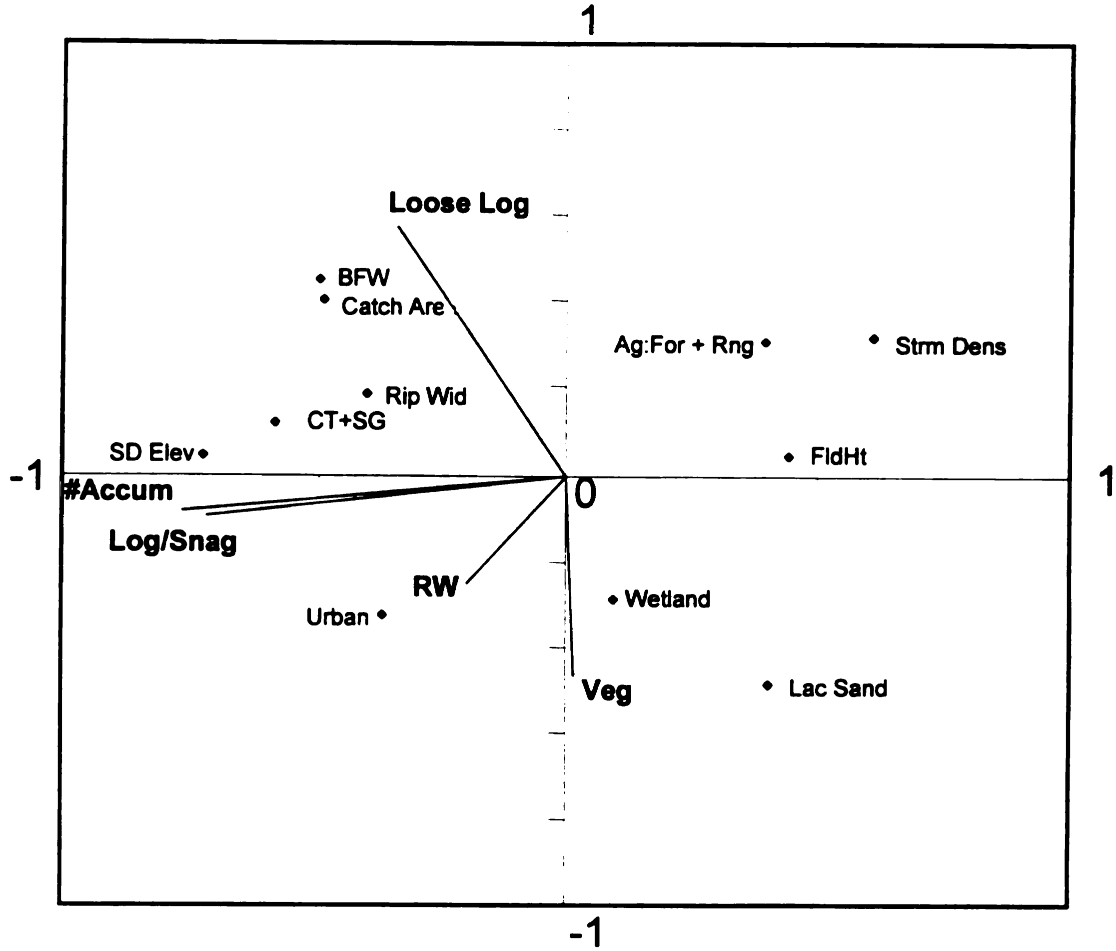


Figure 3-5. Species-environment biplot derived from species scores from a redundancy analysis of debris accumulation types and landscape, riparian and local variables including catchment area (catch area), SD elevation (SD elev), stream density (Strm Dens), % urban (urban), % wetland (Wetland), Agriculture:Forest+Range (Ag:For+Rng), lacustrine sand (Lac Sand), lacustrine clay, coarse till + sand and gravel (CT+SG), instream cover, flood height (Fld Ht), % slow units, maximum depth in slow units, mean bank-full width (BFW), % open canopy, and riparian zone width (Rip Wid).

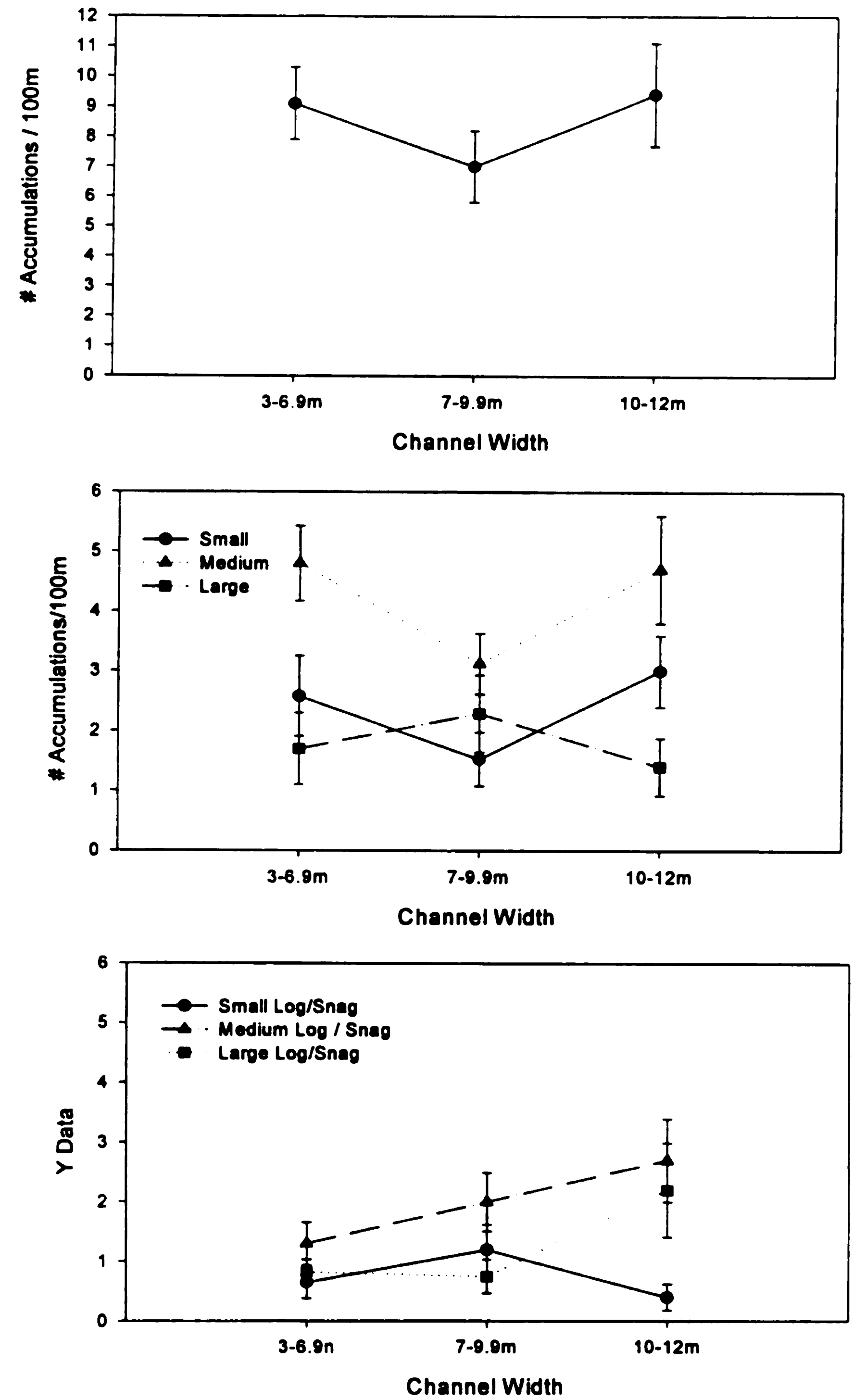


Figure 3-6. A. Mean and SEM of the number of debris accumulations across three channel width classes. A. All accumulation types and sizes combined. B. Accumulations grouped by size. C. 'Log / snag' accumulations grouped by size. Note change in Y-axis scale between A and B, C.

CHAPTER 4

COARSE WOODY DEBRIS RETENTION AND RECRUITMENT IN LOW GRADIENT, MIDWESTERN WATERSHEDS

Abstract

Coarse woody debris (CWD) is an important component of many small to medium-size temperate streams, directly influencing many ecosystem properties and processes. Much is known about the importance of wood in mediating hydrological, geomorphological, and ecological processes of forested streams, however, retention and recruitment dynamics of coarse woody debris in streams are poorly understood. CWD retention and (upstream) recruitment were examined in 10 low-gradient Midwestern streams before and after a 5-year flood event. Effects of channel morphology and log size on retention and recruitment also were examined. Although there was a turnover of approximately 50% of the logs at a site, the number of logs present before and after the flood remained approximately equal. However, log volume was greater before the flood than after. The ratio of retained to recruited logs was <1, indicating that the population of logs after the flood was dominated by recruited rather than retained logs. Log retention and recruitment is in dynamic equilibrium, and the logs exhibiting the greatest movement are the smaller logs. CWD retention and recruitment were successfully predicted from logistic regression models from log dimensions with concordance values ranging from 62 - 68%. Flood height was positively correlated with recruitment and negatively correlated with retention. Retention and recruitment, however, were not correlated with estimates of stream power and shear stress. Bankfull width was negatively correlated with the proportion of logs retained, and positively correlated with the proportion exported and recruited. It appears that rough estimates of these processes can be derived from an estimate of flood height.

Introduction

Coarse woody debris (CWD) is an important component of many small to medium-size temperate streams, directly influencing stream geomorphology as well as many ecosystem properties and processes (see reviews by Harmon, et al. 1986, Gurnell, et al. 1995). In non-forested catchments potential inputs of CWD are reduced by disturbances to the riparian vegetation and stream clearing activities which eliminate CWD from the channel. Land use conversions, installation of drain tiles in agricultural fields, wetland drainage, and stream channelization alter the hydrologic regime, resulting in higher peak flows and 'flashy" hydroperiods. Interactions between management practices and hydrologic factors contribute to low CWD standing stocks (Johnson 1999*a*) and potentially to reduced retention in streams impacted by agricultural land use.

Retention and recruitment dynamics of coarse woody debris in streams have been poorly studied, despite the fact that much is known about the importance of wood in mediating hydrological, geomorphological, and ecological processes of forested streams. The hydraulic significance of large woody debris in stream channels has been well-studied (see reviews by Harmon, et al. 1986, Gurnell, et al. 1995), but the dynamics of wood movement have not. Retention and recruitment of woody debris are important processes that must be characterized to fully understand the factors controlling habitat and biotic community structure of these stream ecosystems. Recent studies by Braudrick, et al. (1997) and Braudrick (1997) have characterized wood movement under different flow regimes, and have attempted to model wood transport as a function of discharge.

Bilby (1984), Lienkaemper and Swanson (1987), and Berg, et al. (1998) have reported interactions between channel width or structure (e.g., channel roughness) and log dimensions with respect to CWD movement. Others have simulated transport and retention of wood using dowel rods or equivalents over short (Ehrman and Lamberti 1992, Hax and Golladay 1998), and longer time frames (Jones and Smock 1991, Webster, et al. 1994). Retention is closely linked to the number and type of obstacles in the channel, and to the size of the log relative to the size of the channel (Bilby 1984, Webster, et al. 1994). In the dowel rod release experiments conducted at the Coweeta Hydrologic laboratory, dowel rods remained generally stable after a period of initial movement. Similarly, wood released in the channels of two low gradient streams in Virginia were recruited into the floodplain the first time there was bank overflow. Interestingly, movement distances in the floodplain exceeded those in the channel in one of the two streams because of retention in debris dams within the channel (Jones and Smock 1991).

Streams in the Saginaw Basin in Michigan are characterized by low standing stocks of CWD, and moderate numbers of debris accumulations (Johnson 1999*a*). Because of the generally homogeneous nature of the stream channels of many of these streams, woody debris accumulations are associated with the banks, rather than structures such as boulders and root wads (Johnson 1999*b)*. As a result, debris accumulations appear to be transient. During three years of field work in this region, several large debris accumulations present at the onset of this work were dismantled following a storm event with a 5-year return interval (*http:\waterdata. USGS.gov)*. Further, many large branches were delivered to the stream channel following intense summer storms. These branches remained loosely distributed throughout the stream reaches throughout the open water season in 1996. These observations suggest that CWD is much more mobile in these streams compared to those studied in higher gradient, forested systems (e.g., Bilby 1984, Webster et al. 1994). This study examined CWD retention and recruitment in 10 stream reaches in an agricultural landscape in the Midwestern USA and addressed two hypotheses: 1) CWD movement in streams of non-forested landscapes is influenced by log size, channel dimensions and flow characteristics, and 2) the location, orientation, and spatial relationship with other woody debris influences CWD movement.

Study Region

The Saginaw Bay catchment of Lake Huron encompasses a 16,317 km^2 region, characterized by sand and clay-dominated lowlands rimmed by coarse-textured glacial features such as ground moraines and outwash plains. The study region is contained within two major ecoregions as defined by Omernik and Gallant (1986): the Southern Michigan/Northern Indiana Till Plains and the Huron/Erie Lake Plain. Each is subdivided into two sub-regions. Soils in the lake plain are dominated by medium and fine-textured loams ranging to clays, with sand in the outwash plains and channels. These clay regions are extensively drained by artificial drainage and tile systems. The periphery of the basin contains many coarse-textured glacial features such as ground moraines and outwash plains. The till plain exhibits the greatest variation in basin topography and contains a high percentage of forested land intermingled with agricultural land and old fields; elevations average about 278 m. The entire drainage was logged for white pine and hemlock between 1830 and 1900, and forests of the region now consist primarily of second growth hardwood species. Current land use is dominated by agriculture. Ten streams reaches in 8 rivers were selected to span a range of land use and Quaternary geology typical of this region (Appendix 4-1, 4-2). Substrates are quite homogeneous and are composed mainly of sands and silts. One site has large boulders at one end of the reach; however, all are submerged and were never observed to trap CWD.

Methods

Woody debris retention and recruitment were measured in ten stream reaches. Logs greater than 5 cm diameter and 1 m length were individually measured and marked with pre-numbered tags during base flow conditions in October 1995. Location of each log was recorded with respect to a known location in the reach. Ancillary information including log orientation with respect to flow (parallel, perpendicular, diagonal), location with respect to the banks (left, right, center, spanning channel), and whether the log was included in a debris dam was also recorded. The goal was to tag at least 50 logs in each stream reach. If less than 50 logs were present in the reach, all logs in the reach were tagged. When a study reach contained more than 50 suitable logs, 5 m stream segments were randomly sampled until at least 50 logs were tagged. A total of 394 logs were tagged across 10 reaches. During the second visit following the spring flood, the location and orientation of each tagged log was noted, along with the location, size, and orientation of newly recruited (untagged) logs. If a log was found within 5m of its original location in the channel it was considered to be 'retained'. Logs were considered 'exported' if they had moved more than 5m from their original location. New logs within a reach, including logs exported from upstream, were considered to be 'recruited'. During the post-flood period in June 1996, 376 logs were measured. Woody debris data were summarized as 1) proportion of original number of logs and wood volume either retained or exported, 2) proportion of newly recruited log number and volume, 3) the ratio of log number and volume at T_1 and T_2, and 4) the ratio of log number and volume retained to recruited. Arcsin transformations were used for proportional data (sqrt (x / 100)) where necessary; log transformations were performed on other non-normal variables by taking the natural log of the datum plus ½ the lowest non-zero value. Differences between means of log number and log volume retained versus exported were tested using a paired T-test (Table 4-1).

In addition to woody debris, channel features including bank-full width, bank-full depth, and percent of channel with fast and slow units were measured (Appendix 4-2). Standing stocks of coarse woody debris in the reach were measured as length of CWD per unit area (m/m^2), volume (m^3/m^2), and number of debris accumulations / 100m (see Johnson 1999*a* for details on measurement methods; Appendix 2-3). Mean log diameter and length of all wood $\geq$ 5 cm diameter were recorded. Flow characteristics including an estimate of stream power and shear stress at flood stage (Gordon, et al. 1992), and an estimate of flood height were measured. A logistic regression was performed to predict whether or not a log is retained or recruited based on log dimensions and volume. Linear regression models were used to predict the actual proportion of retention or recruitment using independent variables identified by the logistic regression (above). To identify those features contributing to the dynamics of wood transport, a Pearson correlation was performed between retention/recruitment variables and 1) flow characteristics, 2) channel morphology, and 3) standing stocks and dimensions of CWD throughout the reach (Table 4-2).

Results and Discussion

Retention and Recruitment

Approximately 60 % of tagged logs, representing about 50 % of the log volume, moved more than 5 m between the two sampling periods (Table 4-1). Although the proportion of the original logs retained was not significantly different from the proportion of logs exported or recruited, the ratio of retained to recruited logs was less than one, indicating that the population of logs after the flood (T_2) was dominated by recruited rather than retained logs. This suggests that CWD retention and recruitment is in a dynamic equilibrium, characterized by a highly mobile pool of logs that are replaced with wood from upstream sources. In contrast, the proportion of log volume per reach was greater before the flood (T_1) than after (T_2), and the ratio of retained to recruited log volumes following the flood was high (Table 4.1), suggesting that larger logs were retained, while smaller logs were recruited. Not surprisingly, the logs exhibiting the greatest movement are the smaller logs. These results are consistent with flume studies of Braudrick, et al. (1997) and observations from field studies (Bilby 1984, Berg, et al.

1998). Studies with small pieces of artificial woody debris (dowel rods), however, showed that there is little movement of these pieces after the initial pulse (Webster, et al. 1994). Releases in that study took place in very small forested streams in the Appalachian Mountains where, in contrast to the current study, streams contained large standing stocks of CWD and CPOM.

Predicting Log Transport

The probability that a log was retained at its original location was successfully predicted from log dimensions. (Table 4-2). Using a logistic regression log(diameter), log(length), and log(volume) successfully predicted whether a log was retained, with concordance values of 62-68%, based on 443 observations. These models are consistent with those of Bilby (1984), who also found that the probability of movement was related to the length and diameter of the log. The geometry of the log (e.g., branching patterns), as well as the extent of burial were confounding factors influencing wood movement. The distance traveled also was related to log length, but not to log diameter.

The current study was not designed to explicitly test the issue of transport distance; however, a sufficient number of logs were recovered to test for the effect of channel features on transport distance. A significant regression model was obtained from measures of steam power and substrate characteristics; however, R^2 values were very low (2% of variance explained). Bilby (1984) suggested that log geometry plays a role in transport distance. Log geometry is likely to play a larger role in the Saginaw streams than elsewhere because many of the "logs" in the stream are actually large branches that have recently fallen from overhanging trees during summer storms. These "logs" have complex geometries, with many branches still intact. These data may therefore not predict transport distance well because of the complex structure of the logs being transported. Clearly, a more robust analysis of transport distance would require peak flow measures over the time period between the two sampling events, and more frequent sampling to capture transport as a function of individual events. A lack of stream gages on these rivers precludes obtaining accurate discharge measurements. Such information would be invaluable for developing accurate models of transport and retention dynamics for CWD.

Log dimensions interact with channel morphology and flow regime in the regulation of log transport/retention dynamics. To identify those features contributing to the dynamics of wood transport, a Pearson correlation was performed between retention/recruitment variables and 1) flow characteristics, 2) channel morphology, and 3) standing stocks and dimensions of CWD throughout the reach (Table 4-3). Flood height was the only flow variable that was significantly correlated with retention/recruitment data. A linear regression predicting the proportion of logs retained from log(flood height) explained approximately 52% of the variance (Figure 4-1a). A similar analysis predicted 65% of the variance in the proportion of logs recruited from log(flood height) (Figure 4-1b). Webster and colleagues (1994) found a significant relationship between stream depth and distance which artificial leaves traveled. The effect of discharge on retention was believed to operate through differences in depth, rather than differences in stream power. However, no significant correlations were observed between retention or recruitment and depth variables in the current study. Poor relationships between stream power and CPOM retention have been observed by others (e.g., Naiman 1982, Minshall, et al. 1992).

Bankfull width (BFW) was the best predictor of retention/ recruitment dynamics (Figure 4-1a,b); indeed, the proportion of number of logs retained, exported, and recruited were all significantly correlated with BFW (Table 4-3). The negative correlation between retention and BFW is consistent with previous work (e.g., Bilby and Ward 1989, Gregory et al. 1993) confirming that smaller channels are more retentive of CWD than larger channels. In contrast, the proportion of log volume retained and exported were poorly predicted by bank-full width and flood height, but were significantly correlated with the standing stocks of CWD and log dimensions. Log volume recruited, however, was the only significantly correlated with BFW. Similarly, the ratio of log number at T_1 to T_2, and the ratio of the number of logs retained to recruited was correlated with BFW, whereas log volume ratios were primarily correlated with CWD standing stocks and wood dimensions, implying that sites with larger standing stocks experience less CWD turnover. Log volume measures all exhibited much larger coefficients of variation (c.v.) than did measures based on log number. These data suggest that there are large variations across sites with respect to CWD transport and retention dynamics that are not related to channel width or flow variables.

The location, orientation in the channel, and inclusion in a debris dam also did not influence whether a log was retained in the reach. Ehrman and Lamberti (1992) found that in stream reaches with little CWD, dowel rods were retained by root wads, stream banks, and single pieces of woody debris in the channel. Three of the ten streams in the current study had been channelized; as a result flow patterns are homogeneous across the reach and have relatively little resident CWD. This is in contrast to other sites with well-developed pool riffle sequences, and moderate accumulations of CWD that enhance retention.

Conclusions

Retention and recruitment dynamics of coarse woody debris in low gradient, agricultural streams were examined with respect to channel and flow characteristics. These sites have modest standing stocks of relatively small coarse woody debris and, in general, exhibit stream profiles consistent with disturbed systems. CWD in these streams appears to be highly mobile, with approximately 50% of the logs turning over between the two sampling periods before and after modest spring floods. As anticipated, larger volume logs are less mobile than smaller logs. Retention and recruitment, surprisingly, was not significantly correlated with estimates of stream power and shear stress during flood conditions. Rather, these processes were most highly correlated with flood height and bankfull width. Channel dimensions have long been known to influence the transport dynamics of coarse woody debris. It now appears that rough estimates of these processes can also be derived from a simple estimate of flood height. Managers who are considering restoration methods involving addition of CWD to the stream may be interested in predicting the amount of wood that is expected to be retained or transported under different flow conditions. Additional work, including deriving better measures of peak flow on these ungauged streams should enhance our predictive powers.

Table 4-1. Descriptive statistics for the proportion of logs and log volumes from T_1 retained (retention) and the proportion of newly recruited logs and log volumes measured at T_2. Ratios of logs at each sample period, recruited to exported, and retained to recruited also are shown.

Variable		Mean $\pm$ S.E.M.	Range
Proportion Retained	# Logs	0.42 $\pm$ 0.06	0.15 - 0.73
	Volume (m^3/m^2)	0.52 $\pm$ 0.09	0.07 - 0.88
Proportion Recruited	# Logs	0.58 $\pm$ 0.05	0.37 - 0.75
	Volume (m^3/m^2)	0.36 $\pm$ 0.05	0.12 - 0.69
Proportion Exported	# Logs	0.58 $\pm$ 0.06	0.06 - 0.44
	Volume (m^3/m^2)	0.48 $\pm$ 0.09	0.12 - 0.92
T1 : T2	# Logs	1.03 $\pm$ 0.11	0.63 - 1.63
	Volume (m^3/m^2)	1.46 $\pm$ 0.33	0.69 - 4.23
Retain : Recruit	# Logs	0.80 $\pm$ 0.18	0.33 - 1.80
	Volume (m^3/m^2)	2.12 $\pm$ 0.66	0.45 - 7.62

Table 4-2. Logistic regressions predicting whether or not a log is retained from log dimensions and volume. CCR % = percent correctly classified. (N = 443 logs).

Variable	Parameter Estimate	S.E.M.	adj R^2	CCR(%)
log (length)	0.72	0.15	0.07	62.4
log(diameter)	1.12	0.22	0.09	63.0
log(volume)	0.42	0.08	0.10	66.6

Table 4-3. Pearson correlation coefficients for wood retention and recruitment versus flow and channel characteristics, including standing coarse woody debris per 100 m reach (see Johnson 1999*a* for a description of methods), and mean dimensions of logs in the reach. The proportion of logs and log volume exported are inversely related to the proportion retained and are not listed in this table. (Significant coefficients in bold are corrected using Bonferroni methods.)

Wood Variable (n=10)		Log (Flood Height)	% Slow Units	Log (Bankfull Width)	m CWD / 100 m	Mean Log Diameter	Mean Log Length
Proportion Retained	# Logs	**-0.72**	-0.37	**-0.86**	-0.61	**-0.82**	**-0.66**
	Volume	-0.44	-0.18	-0.45	**-0.62**	-0.61	-0.36
Proportion Recruited	# Logs	**0.81**	0.12	**0.77**	0.48	**0.72**	**0.66**
	Volume	0.60	0.56	**0.67**	**0.66**	**0.64**	0.36
T1 : T2	# Logs	0.24	**0.79**	**0.68**	0.43	0.29	-0.06
	Volume	0.43	0.42	0.58	**0.72**	0.42	0.06
Retain : Recruit	# Logs	**-0.74**	-0.12	**-0.71**	-0.50	**-0.80**	**-0.81**
	Volume	-0.46	-0.22	-0.47	-0.50	**-0.87**	**-0.75**

Appendix 4-1. Description of catchments and streams.

Site	Catchment Area (ha)	Stream Order	Link Number	Mean Catchment Slope (%)	Mean Catchment Elevation (m)	Stream Density (km/km^2)	Flood Height (m)
51	7813.1	3	12	0.531	227.8	0.768	2.5
91	7375.3	2	12	0.273	192.9	0.914	3.4
93	2825.8	2	5	0.44	203.1	1.123	3.3
321	3538.3	3	5	0.613	218.9	0.740	1.2
323	1715.7	2	2	0.646	223.4	0.631	1.2
353	9239.9	1	8	1.556	317.0	0.523	1.2
363	3855.5	2	2	0.661	270.9	0.712	0.87
2411	21890.0	3	30	0.518	235.6	1.273	3.3
2413	12265.8	3	23	0.465	236.8	1.293	2.3
5121	4370.7	2	9	0.144	200.0	0.882	1.3

Appendix 4-2. Description of channel-scale properties.

Site	%Fast Units	% Slow Units	Max Depth Slow Unit (m)	Max Depth Fast Unit (m)	Avg Width Wetted Channel (m)	Avg Depth Wetted Channel (m)	Mean Bank-Full Width (m)	Mean Bank-Full Depth (m)
51	0.72	0.27	0.91	0.52	6.63	0.51	8.00	0.85
91	0.84	0.16	0.67	0.58	7.04	0.38	8.80	0.95
93	0.87	0.13	1.01	0.76	5.55	0.59	6.93	0.88
321	1.00	0.00	0.00	0.76	5.13	0.42	6.58	0.45
323	1.00	0.00	0.00	0.40	4.83	0.26	6.63	0.85
353	0.78	0.22	0.88	0.37	4.71	0.41	5.77	0.62
363	0.85	0.15	0.49	0.12	3.40	0.06	5.90	0.56
2411	0.00	1.00	0.91	0.00	10.22	0.56	11.47	0.73
2413	0.00	1.00	0.79	0.00	8.97	0.55	10.13	0.65
5121	0.00	1.00	0.73	0.00	4.91	0.50	5.99	0.56

Appendix 4-3. Wood debris abundance measures.

Site	CWD abundance (m/m^2)*	CWD volume (m^3/m^2)	Mean Log Diameter (m)	Mean Log Length(m)	# Debris Accum/100m
51	0.437	0.0017	0.075	2.82	10
91	0.690	0.0032	0.107	4.98	8
93	0.268	0.0008	0.084	1.88	7
321	0.680	0.0042	0.096	3.27	15.6
323	0.340	0.0068	0.110	4.04	9
353	0.361	0.0015	0.150	0.80	9
363	0.496	0.0020	0.067	1.50	6
2411	0.567	0.0128	0.099	2.50	7
2413	0.070	0.0029	0.072	1.51	4
5121	0.406	0.0003	0.050	0.75	8

* see Johnson (1999*a*) for details of the calculation of these variables.

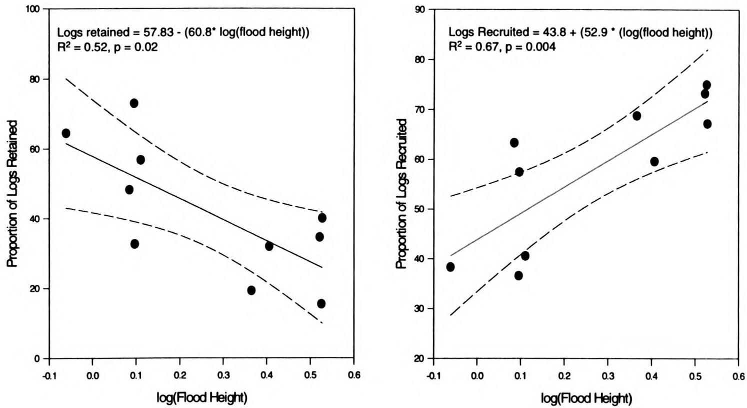


Figure 4.1. Regression analysis predicting the proportion of logs retained and recruited as a function of the log(flood height).

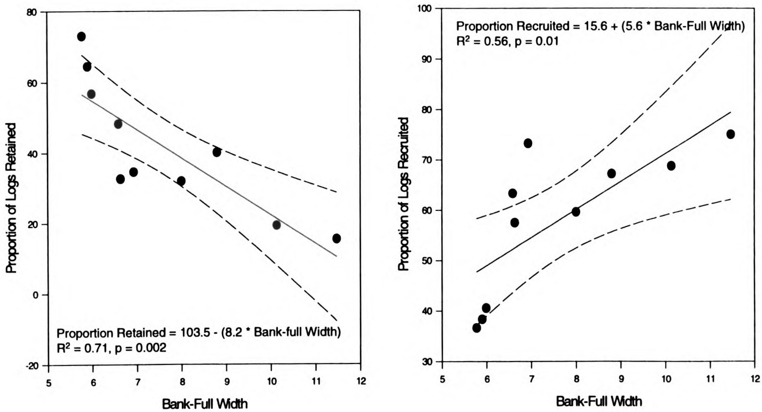


Figure 4.2. Regression analysis predicting the proportion of logs retained and recruited from bank-full width.

CHAPTER 5

MACROINVERTEBRATE COMMUNITY STRUCTURE AND FUNCTION ASSOCIATED WITH COARSE WOODY DEBRIS IN LOW GRADIENT, MIDWESTERN STREAMS

Abstract

Coarse woody debris (CWD) plays a number of important roles in forested stream ecosystems, including providing habitats for fish and invertebrates, flow refugia, and a site of biofilm production that serves as food for grazing organisms. Logs added to streams are rapidly colonized by invertebrates, and the changes in associated habitats are accompanied by changes in community composition and functional attributes. A multiple habitat, qualitative sampling approach was employed to evaluate macroinvertebrate communities associated with woody debris accumulations in 36 stream reaches in low gradient Midwestern streams. Taxa were classified with respect to habit (e.g., sprawler, clinger, swimmer) as well as trophic/feeding characteristics. These traits were used to examine community structure as a function of coarse woody debris abundance and distribution. Two taxa, the amphipod *Hyallela* and chironomid *Polypedilum*, made up 23% of the total abundance of organisms found in association with woody debris. The mayfly, *Caenis* and elmid *Dubiraphia* made up an additional 11% of the individuals in the woody debris community. Individuals belonging to the most common 9 taxa made up 52% of the woody debris community. Although woody debris is not abundant in these streams, it is one of the most important habitats for macroinvertebrates in the streams of the Saginaw Basin. Since woody debris can occur in both fast and slack water, the taxa found in association with wood habitats span a range of current preferences, as well as functional and habit traits. The patterns in the distribution of habit and functional traits within wood habitats suggests that these traits may vary with the location of woody debris in the channel relative to the flow regime.

Introduction

Macroinvertebrate community structure and function are influenced by a complex array of abiotic and biotic factors that interact over a range of spatial and temporal scales (Carter, et al. 1996, Richards, et al. 1996, 1997). At the reach scale, abiotic factors such as local flow regime (Stratzner and Higler 1986, Brown and Brussock 1991), substrate composition (Erman and Erman 1984, Wood and Armitage 1997), substrate stability (Cobbs, et al. 1992, Death 1995), and the presence of coarse woody debris (Benke, et al. 1984, 1985, Wallace, et al. 1995) play a strong role in structuring macroinvertebrate community structure and function. Coarse woody debris (CWD) plays an important role in forested stream ecosystems as a geomorphological agent, increasing flow heterogeneity through retardation of flow and creation of plunge pools (Keller and Tally 1979; Robison and Beschta 1990), changing channel depth and form (Nakamura and Swanson 1993; Richmond and Fausch 1995), and increasing organic and inorganic matter retention (Smock, et al. 1989; Beechie and Sibley 1997). CWD also plays an important role as nursery habitat for salmonids (Murphy, et al. 1986; McMahon and Hartman 1989), perching habitat for invertebrates (Angermeier and Karr 1984; O'Connor 1992), and a site of biofilm production that serves as food for grazing invertebrates (Hax and Golladay 1997, Bowen, et al. 1998). Logs added to streams are rapidly colonized by a wide range of invertebrates (Nilsen and Larimore 1973, O'Connor 1991, Hilderbrand, et al. 1997), and the change in associated habitats (i.e., pools formed from the erosive action of stream flow around the logs) is accompanied by changes in community composition and functional attributes. Ephemeroptera abundance increased in pools associated with log additions, while Plecoptera, Coleoptera, Trichoptera and Oligochaete abundance decreased (Hilderbrand, et al. 1997). Large changes in biomass and abundance of functional groups followed the addition of logs to riffles in a high-gradient stream (Wallace, et al. 1995). In the littoral zone of two Canadian lakes, differences in functional groups on natural and introduced logs were attributed to biofilm chlorophyll *a* concentrations (Bowen, et al. 1998).

In a study relating catchment and reach-scale characteristics of 58 catchments in central Michigan, to macroinvertebrate taxon traits, the presence of coarse woody debris was positively associated with the presence of large bodied insects and clinging macroinvertebrates (Richards, et al. 1997). Feeding traits (shredders) and habit modes (swimmers, climbers, sprawlers) responded negatively to the percent of open canopy cover, which also is correlated with the amount of CWD in the stream (Johnson 1999*a*). In a related study, the presence of CWD, percent of reach with deep pools and the percent of fine sediments in the substrate were positively associated with the presence of macroinvertebrate predator taxa found exclusively in depositional habitats, and negatively associated with the proportion of taxa found exclusively in erosional habitats, and the proportion of the taxa belonging to Ephemeroptera, Plecoptera, or Trichoptera (EPT) families (Richards, et al. 1996).

Coarse woody debris is being widely used in stream restoration to improve fish habitat (Hunter 1995); however, little is known about the role that CWD may play in structuring the macroinvertebrate community in highly altered streams with few stable, hard substrates. The focus of the above studies by Richards, et al. (1996, 1997) was to quantify associations among macroinvertebrate taxa or macroinvertebrate taxon traits and a suite of landscape and habitat-scale variables. These studies identified woody debris as a potentially important local and regional factor influencing macroinvertebrate community structure and function. The current study was designed to specifically address the relationships between CWD abundance and distribution with respect to the compositional and functional attributes of the macroinvertebrate community. The goals of this study are to: 1) identify compositional, life history, and behavioral habits of the macroinvertebrate community that are most closely associated with CWD; 2) contrast structural differences in the communities on wood habitats versus those of other habitats; and 3) quantify the effect of CWD abundance and distribution on macroinvertebrate community structure and function in non-forested streams.

Methods

Study Area

The Saginaw Bay catchment of Lake Huron encompasses a 16,317 km^2 region, characterized by sand and clay-dominated lowlands rimmed by coarse-textured glacial features such as ground moraines and outwash plains (Figure 1-1). The study region is contained within two major ecoregions as defined by Omernik and Gallant (1986): the Southern Michigan/Northern Indiana Till Plains and the Huron/Erie Lake Plain. Each is subdivided into two sub-regions. Soils in the lake plain are dominated by medium and fine-textured loams ranging to clays, with sand in the outwash plains and channels. These clay regions are extensively drained by artificial drainage and tile systems. The periphery of the basin contains many coarse textured glacial features such as ground moraines and outwash plains. The till plain exhibits the greatest variation in basin topography and contains a high percentage of forested land intermingled with agricultural land and old fields; elevations average about 278 m. The entire drainage was logged for white pine and hemlock between 1830 and 1900, and forests of the region now consist primarily of second growth hardwood species. Three first to third order reaches in each of 12 catchments were selected to quantify some internal variation in dominant land use and surficial geology within streams. A total of 36 subcatchments ranging in size from 712 to 23,448 ha were studied (Figure 5-1). Sample reaches were located at least 50 m upstream of bridges and culverts.

Coarse Woody Debris

Coarse woody debris assessments were performed during low flow conditions during the summer of 1995. CWD volume was measured using the line transect method (Wallace and Benke 1984). Volume per unit area was calculated for each transect and summed for each reach (see Johnson 1999*a* for details of sampling methods). In addition to volume measurements, counts of the total length of CWD $\geq$ 0.05 m diameter and $\geq$ 1 m in length were made at 10 m intervals within the reach and summarized as total meters of wood per m^2 of stream bottom (m/m^2) for each site. Debris accumulations $\geq$ 1 m^2 in area were counted and summarized as the total number of debris accumulations / 100 m reach.

Debris accumulations were broadly defined to include overhanging vegetation with trapped debris, root wads with attached debris, loose log accumulations, as well as debris jams (see Johnson 1999*b* for details). Debris accumulations were assigned a size class based on the dimensions of the accumulation relative to the width of the stream (Shields and Smith 1992); the amount of stream channel covered by debris accumulations also was recorded (= sum accumulation size; see Johnson 1999*a*).

Macroinvertebrate Community

A multiple habitat approach as described by Lenat (1988) was employed to evaluate macroinvertebrate communities associated with major subhabitats including erosional and depositional areas, shorelines, leaf packs, and woody debris. This technique reduces bias encountered in single habitat sampling techniques (Kearns, et al. 1992) and allows a larger number of sites to be evaluated. The approach employs a variety of sampling devices (timed kick net samples, Ekman samplers) and effectively samples a high diversity of organisms across size categories (Lenat 1988). Five different habitats types were examined in this analysis: pools, runs, riffles, macrophyte beds, and woody debris accumulations. Three replicate samples were obtained from each habitat type. Sampling was conducted once during late summer or early autumn when the largest number of invertebrates (with the exception of shredders) were of sufficient size for clear identification to generic level. Sampling in the wood habitats was achieved by vigorously agitating wood accumulations and capturing displaced organisms with the dipnet. This methodology not only captured organisms associated with the wood itself, but also captured planktonic organisms in slack water associated with log accumulations.

Samples were preserved and returned to the laboratory for processing and identification. Large pieces of inorganic and organic matter were removed and the remaining material was spread over shallow trays with grid lines. Organisms were removed from randomly selected grids until 100 individuals were obtained or the entire sample was processed. Taxa were classified with respect to trophic/feeding categories, as well as habit (as per Merritt and Cummins 1996). These traits were used to examine community structure as a function of coarse woody debris abundance and distribution (as per methods in Richards, et al. 1997).

To assess the compositional and functional aspects of the macroinvertebrate community associated with CWD, taxa were classified according to their affinity for the woody debris habitat as "wood-associated" (found exclusively in wood habitat samples), "wood-dominant" (> 90% of individuals encountered in the wood habitat samples), "wood-averse" (less than 10% of individuals associated with woody samples), and "wood-absent" (taxon never found in association with woody samples). Taxon traits were summarized as a proportion of the pool of wood-associated/dominant or wood-averse/absent taxa (n = 55 taxa). To determine whether there were significant differences in taxon traits within the wood habitat samples, a one way analysis of variance was performed on the proportion of individuals associated with each class of traits (e.g., habit and functional feeding).

The contribution of CWD habitats to the macroinvertebrate community at each site compared to all other habitats was examined by comparing the number of taxa associated with woody debris habitats with taxa richness values derived from all other habitat types combined (Appendix 5-2). The number of unique taxa contributed by wood was derived from the difference between the number of taxa contributed by the CWD habitats and the taxa richness from all other habitat types combined. A Pearson Product Moment Correlation test was performed between the number of unique taxa contributed by CWD habitats and all other habitats and CWD abundance metrics, log (m/m2), log (volume), number of debris accumulations / 100 m, and sum accumulation size (see Johnson 1999*a* for a description of methods).

Results

Wood debris habitats were present at 31 of the 36 stream reaches sampled (Table 5-1). Twenty four wood-associated taxa and eleven wood-dominant taxa were found across the study area (Appendix 5-1). The wood-dominant taxa each occurred in much greater abundance than the wood-associated taxa. The taxa that are most closely associated with woody debris are distributed among eight insect orders, in addition to nematode and naidid worms. The most abundant wood-associated taxa found were: *Enallagma* (Coenagrionidae), *Anopheles* (Culicidae), *Matus* (Dytiscidae), *Belostoma*

(Belostomatidae), *Cyphon* (Helodidae), *Hydraena* (Hydraenidae), *Paraponyx* (Pyralidae), and *Boyeria* (Aeschnidae). Most of the wood-associated taxa were very rare in the study area; only five taxa, *Plea* (Pleidae), *Brillia* (Chironomidae), *Platycentropus* and *Limnephilus* (Limnephilidae), and *Lype* (Psychomyiidae) were represented by more than 5 individuals in the entire collection. Twenty one wood-averse taxa and four wood-absent taxa occurred in the study area (Appendix 5-1). Wood-averse taxa with the exception of *Atherix* sp. (Athericidae) were rare.

The most common taxa found in the woody debris habitat samples were the amphipod *Hyallela* and chironomid *Polypedilum*, composing 23% of the total abundance of organisms in this habitat (Table 5-2). The elmid, *Dubiraphia,* and mayfly, *Caenis* composed an additional 11% of the individuals in the woody debris habitat. Individuals belonging to the nine most common taxa compose 52% of the woody debris community.

Traits Associated with Wood-Dominant and Wood-Averse Taxa

Of the 55 taxa that were either wood-associated/averse or wood-absent/averse, 45% percent were classified as predators, 25% as collectors, and 18% as shredders, and 5% as scrapers (Table 5-3). Collector taxa were approximately equally represented between the wood-associated/dominant and wood-averse/absent groups. In contrast, there were more scraper taxa in the wood-absent/averse group, while there were more shredders and predators in the wood-associated/dominant group. The five habits were approximately equally represented across these 55 taxa. The most common habit modes of the wood-associated/dominant taxa were climbers and clingers, with swimmers and burrows having somewhat smaller representation (Table 5-4). Sprawlers were most common and climbers were absent amongst the wood-averse/absent taxa. The proportion of borrowing and clinging taxa were approximately equal between the wood-averse and wood-associated groups.

Of the nine numerically dominant taxa associated with woody debris habitats, four are collectors (three are collector-gatherers, one is a filter feeder), three are predators, one each are grazers and shredders. Across the entire community associated with woody debris there was a significantly greater proportion of collectors than scrapers, shredders and predators (Figure 5-2a). The proportion of collector-gatherers was greater than collector-filterers (Figure 5-2b). In addition, there was a significantly greater proportion of individuals whose behavior was characterized as clinging forms compared with that of swimming and climbing forms (Figure 5-3).

Influence of CWD Standing Stocks on Macroinvertebrate Community

At 23 sites, the presence of the CWD habitat contributed a mean of 11 $\pm$ 2.3 (range 1 to 28) unique taxa to the total taxa richness (Appendix 5-2). There was a significant correlation between the number of taxa contributed by woody debris habitats and the standing stocks of CWD at a site, as measured by log(m/m^2), and log(volume) (Table 5-5). The log (m/m^2) and sum accumulation size (the metric reflecting the amount of stream channel covered by CWD accumulations) were both negatively correlated with the number of taxa contributed by non-wood habitats.

Discussion

Coarse woody debris is not abundant in these Saginaw basin streams; despite this, woody debris is one of the most important habitats for macroinvertebrates in these streams. Of 150 total taxa encountered across the study region, 130 were found in association with coarse woody debris. Of these 130 taxa, 24 were found only in the woody debris samples, and another 11 taxa were disproportionately represented in the wood samples compared with other sample types. Despite the smaller standing stocks of CWD and the apparent smaller size of debris accumulations compared with forested regions (Johnson1999*b*), woody debris habitats are important contributors to the taxa richness of these streams. At more than half of the sites (22 of 35), the CWD habitat contributes a mean of 11 unique taxa (with a range of between 1 and 28) to the total pool of taxa. Benke, et al. (1984) and Smock, et al. (1985) both report increased production in association with snag habitats in coastal plain rivers where shifting sand substrates otherwise provide few stable habitats. Many streams in this region are severely degraded due to disturbances that began when the region was harvested of white pine and hemlock from 1840-1900. Following this period of intensive harvest, fires burned much of the regions, resulting in a denuded landscape that was then subject to massive soil erosion. Conversion to agricultural land followed in the 1930's when large expanses of wetlands were drained and placed under production (Comer, et al. 1993). Inherent in agricultural production are management practices that involve stream channelization, replacement of woody riparian vegetation with grasses, and stream clearing to remove any obstacles to flow. Superimposed upon these management regimes, which themselves have a tendency to reduce stream habitat heterogeneity, is the effect of the Quaternary geology on the hydrologic regime. Regions dominated by lacustrine sediments, particularly lacustrine clays, tend to have flashy flow regimes due to the intensive tiling in agricultural regions, and the dominance by surface water rather than ground water flow regimes. Even in catchments dominated by mixed, rather than agricultural land use, and morainal geology, the streams are relatively homogeneous compared with more pristine streams in the northwestern and northern part of the state. This homogeneity clearly influences the low standing stocks of CWD (see Johnson, 1999*a*), the paucity of hard surface habitats such as riffles.

At sites where woody debris habitats contributed unique taxa to the overall taxa pool, total taxa richness was lower compared to sites where woody debris did not contribute unique taxa to the pool. The influence of woody debris habitats therefore appears to be greatest when overall taxa richness is low, probably due to low overall habitat heterogeneity or specifically to the absence of other hard substrate habitats at the site. When overall taxa richness is high, the relative contribution of woody debris to the overall taxa pool is lower, due to high habitat heterogeneity which creates the potential for unique taxa to be contributed from a variety of habitat types. This interpretation is reinforced by the negative correlation between CWD abundance standing stocks and the number of unique taxa added to the taxa pool from non-wood habitats (Table 5-5). Where woody debris is present in abundance, generalist taxa associated with wood are also found on other habitats, therefore few unique taxa are added when additional habitats are available. Introduction of unique habitats with habitat-specific taxa are necessary to increase the pool of unique taxa.

The number of unique taxa added to the total taxa pool from wood habitats was positively correlated with standing stocks of CWD at a site (Table 5-5). Such a pattern is expected based on species-area curves (as per MacArthur and Wilson 1967, Barbour and Brown 1974), if one considers increasing abundance of CWD to be equivalent to increasing habitat area. Number of unique taxa associated with wood habitats are also positively correlated with mean bank-full width, but not with substrate characteristics or other characteristics of channel structure (e.g., depth, flow characteristics; data not shown). It is not surprising that flow characteristics would not be related to taxa richness. Rather, this feature of streams is more likely to influence the functional and compositional response of the community, through alteration of life history traits (Poff and Ward 1989).

Community Structure and Function

The majority of the 11 numerically dominant taxa found in association with woody debris habitats are habitat generalists and were found in all or most of the sample types studied; *Asellus, Anopheles,* and *Calopteryx* was not found in riffle samples, and

Rheotanytarsus, Paratanytarsus, and Hydropsyche were either rare or absent in pool habitats. With the exception of the coenagrionid, *Calopteryx*, the eleven most common taxa or close relatives, as well as the wood-associated and wood-dominant taxa, have previously been reported to occurr in association with coarse woody debris (Nilsen and Larimore 1973, Dudley and Anderson 1982, Benke, et al. 1984, Smock, et al. 1985, Phillips and Kilambi 1994*a,b*, Bowen, et al. 1998). *Calopteryx* is a widespread genus found in the margins of lotic habitats. This taxon was found exclusively in slack water habitats, including macrophyte beds, pools, and in association with woody debris.

One of the roles ascribed to CWD is that it provides a surface for biofilm development, and thereby serves as a food source for scrapers (Hax and Golladay 1997, Bowen, et al. 1998). To a limited number of xylophagous taxa, the wood itself is a source of nutrition. For the most part, taxa associated with woody debris use it as a resting and feeding platform (Dudley and Anderson 1982). The complexity of the wood bark increases the potential surface area of this habitat, providing a flow and predation refugium (O'Connor 1992). Predators, grazer/scrapers, and filter-feeders could potentially use a hard substrate habitat such as CWD. Among the nine dominant taxa associated with CWD in our streams, three taxa were collector-gatherers; one was a filter-feeder, two were predators, and one each were shredders and grazers. Few of the wood-associated/dominant taxa were designated as collectors; most were predators or shredders.

Since woody debris can occur in both fast and slack water, the taxa found in association with wood habitats span a range of current preferences, as well as functional and habit traits. Within the CWD habitat, there were significant differences in abundance between gatherers and filterers, with gatherers being more abundant than filterers. These patterns are similar to those observed by Wallace, et al. (1995), who reported decreases in biomass and abundance of filterers in log-influenced sections of riffles compared to those with no log additions, whereas collectors (gatherers) increased in abundance and biomass. The effect of the log addition was to decrease flow rates and increase standing stocks of organic matter. The riffle section became more pool-like in its character with the addition of logs to deflect flow. Benke, et al. (1984) and Smock, et al. (1985) also reported high production associated with filter-feeding and collector-gatherer taxa, compared with benthic production and production in the muddy stream banks of lowland rivers. In the Saginaw Basin streams, the variance associated with the abundance of filterers in the woody debris habitats was greater than that for gatherers. This may be related to the flow conditions surrounding the CWD accumulations. Since woody debris can accumulate in slack water, as well as in faster current, filter feeding macroinvertebrates may be responding to the current, as well as the presence of hard substrate.

Among the numerically dominant taxa in this study were the chironomids *Polypedilum* and *Thienemannimyia*, and the coenagrionid *Calopteryx*. The damselfly would potentially account for a large proportion of biomass, due to its large size.

However, this taxa, and *Polypedilum* are associated with slack water habitats, therefore, flow conditions may again be an important determinant of the distribution of this functional group.

Macroinvertebrates have evolved many morphological and habit characters to deal with the effects of flow. The habit related to locomotion would be expressed most strongly across gradients of flow regimes, with pool habitats and macrophytes beds at one end of the spectrum and riffle and run habitats at the other end. Depending on the location of CWD in the channel, the organisms found in association with that habitat might express a range of locomotor traits. Within the woody debris habitat there were significantly more clingers than climbers and swimmers (Figure 5-3). A clinging habit is commonly found among flattened species found in rapid currents, and is commonly associated with organisms living in riffles (Allan 1995). Again, these patterns suggest that the functional/habit composition of the macroinvertebrate community on CWD may vary with its location in the channel relative to the flow regime.

Conclusions

Coarse woody debris in these low gradient, Midwestern streams represents a very important habitat for macroinvertebrates, even though it is not abundant. Much of the overall taxa richness can be attributed to the presence of CWD at a site by providing a pool of taxa that are unique to that habitat. As CWD abundance increases, the potential contribution of taxa from other habitat types decreases. This reflects the tendency of

most taxa to be habitat generalists- in the presence of CWD, taxa occupy that habitat as well as others, reducing the potential contribution of unique taxa from other habitat types.

The community of taxa that occupy CWD habitats are diverse in their behavior and trophic status. While the taxa found only in association with CWD were numerically uncommon, a large proportion of these taxa were predators and shredders. In contrast, the numerical dominants of the community were largely composed of collectors. The turbid nature of the streams in the study area and the lack of other hard substrates may cause these taxa to use CWD disproportionately compared to other types of streams.

Despite the low standing stocks of CWD, the wood that is present appears to play an important role in structuring the composition and the function of the macroinvertebrate community. Many management practices employed across the basin are directed at removing woody debris and other structures that represent obstacles to flow, such as overhanging vegetation. These habitats are important constituents of the stream ecosystem and contribute a large pool of taxa to the overall richness. Attempts should be made to moderate stream clearing practices that reduce structural heterogeneity.

Table 5-1. Abundance of macroinvertebrates from five sample types. Average per samples were derived by dividing the total number of individuals by the number of sites in which the habitat was represented.

Abundance Metric	Wood	Macrophyte	Run	Riffle	Pool
Total # of Taxa	130	80	82	60	80
Total # Individuals	6809	2415	2265	2132	4140
# Sites	31	9	14	10	26

Table 5-2. Taxa forming the numerical dominant members of the macroinvertebrate community present in woody debris samples.

Taxa	Family	Order	# Individ. (Cumul. %)	Trophic Status	Trophic Relations	Habit	Habitat
Hyallela	Talitridae	Amphipoda	977 (14.3%)	Detrit	Grazer	Swim; Climb	Dep
Polypedilum	Chironomidae	Diptera	566 (22.6%)	Omniv	Pred; Shred	Climb; Cling	Dep
Dubiraphia	Elmidae	Coleoptera	438 (29.1%)	Detrit	Col-gath	Cling	Eros
Caenis	Caenidae	Ephemeroptera	361 (34.4%)	Detrit	Col-gath; Scrape	Sprawl	Dep
Paraleptophlebia	Leptophlebiidae	Ephemeroptera	348 (39.5%)	Detrit	Col-gath; Shred	Swim	Eros
Calopteryx	Calopterygidae	Odonata	227 (42.8%)	Carniv	Pred	Climb	Eros/Dep
Cricotopus	Chironomidae	Diptera	219 (46.1%)	Herb	Shred; Col-gath	Cling	Eros/Dep
Rheotanytarsus	Chironomidae	Diptera	206 (49.1%)	Detrit	Col-filt	Cling	Eros
Thienemannimyia	Chironomidae	Diptera	196 (52.0%)	Carniv	Pred	Sprawl	Eros/Dep

Herb = herbivore; Detrit = detritivore; Carniv = carnivore
Col-gath = collector-gatherer; Col-filt = collector-filterer; Graz = grazer; Pred = Predator; Shred = shredder
Climb = climber; Cling = clinger; Sprawl = sprawler; Swim = swimmer
Eros = obligate erosional; Depos = obligate depositional; Eros/Dep = erosional and/or depositional

Table 5-3. Functional feeding groups of taxa strictly associated with coarse woody debris, and taxa averse to coarse woody debris habitats. Macrophyte piercers represented less than 4 % of the total taxa, and taxa with unknown characteristics were about 1.5% of the total pool of taxa in these groups.

Association With Wood Habitats	Feeding Functional Group			
	Shredder	Collector	Scraper	Predator
Overall Total (n = 55)	18.0%	25.0%	5.0%	45.0%
wood-absent (n = 19)	16%	21%	10%	42%
wood-averse (n = 3)	0%	33%	33%	33%
wood-dominant (n = 10)	20%	20%	10%	50%
wood-associated (n = 23)	22%	22%	4%	48%

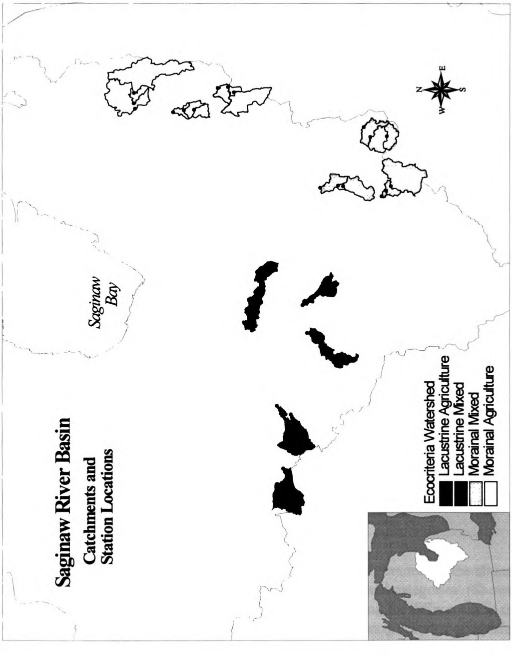
Table 5-4. Habit modes of taxa strictly associated with coarse woody debris, and taxa averse to coarse woody debris habitats. Taxa with unknown characteristics represent about 1.5% of the total pool of taxa in these groups.

Association With Wood Habitats	Habit				
	burrow	climb	cling	sprawl	swim
Overall Total (n = 56)	17.9%	19.6%	23.2%	17.9%	14.3%
wood-absent (n = 19)	7.1%	0.0%	8.9%	8.9%	5.4%
wood-averse (n = 4)	1.8%	0.0%	1.8%	3.6%	0.0%
wood-dominant (n = 11)	3.6%	7.1%	3.6%	0.0%	1.8%
wood-associated (n = 22)	5.4%	12.5%	8.9%	5.4%	7.1%

Table 5-5. Pearson correlation coefficient from number of unique taxa contributed to the total taxa richness from wood and non-wood habitats (pools, riffles, runs, macrophytes) versus standing stocks of coarse woody debris measured as m/m^2, m^3/m^2, and a measure of the amount of channel covered by debris accumulations. Significant values are adjusted by Bonferroni corrections.

Source of Taxa	Log (m/m^2)	Log (m^3/m^2)	SqRt (# debris accum / 100m)	SqRt (Σ accum size)
# Unique Taxa on Non-Wood Habitat	-0.557 ($p = 0.012$)	-0.559 ($p = 0.012$)	-0.437 n.s.	-0.514 ($p = 0.037$)
# Unique Taxa Contributed by Wood Habitat	0.462 n.s.	0.508 ($p = 0.043$)	0.31 n.s.	0.32 n.s.

Figure 5-1. Map of study region.


Saginaw River Basin
Catchments and
Station Locations
Saginaw
Bay
Ecocriteria Watershed
Lacustrine Agriculture
Lacustrine Mixed
Morainal Mixed
Morainal Agriculture
N
E
S
W

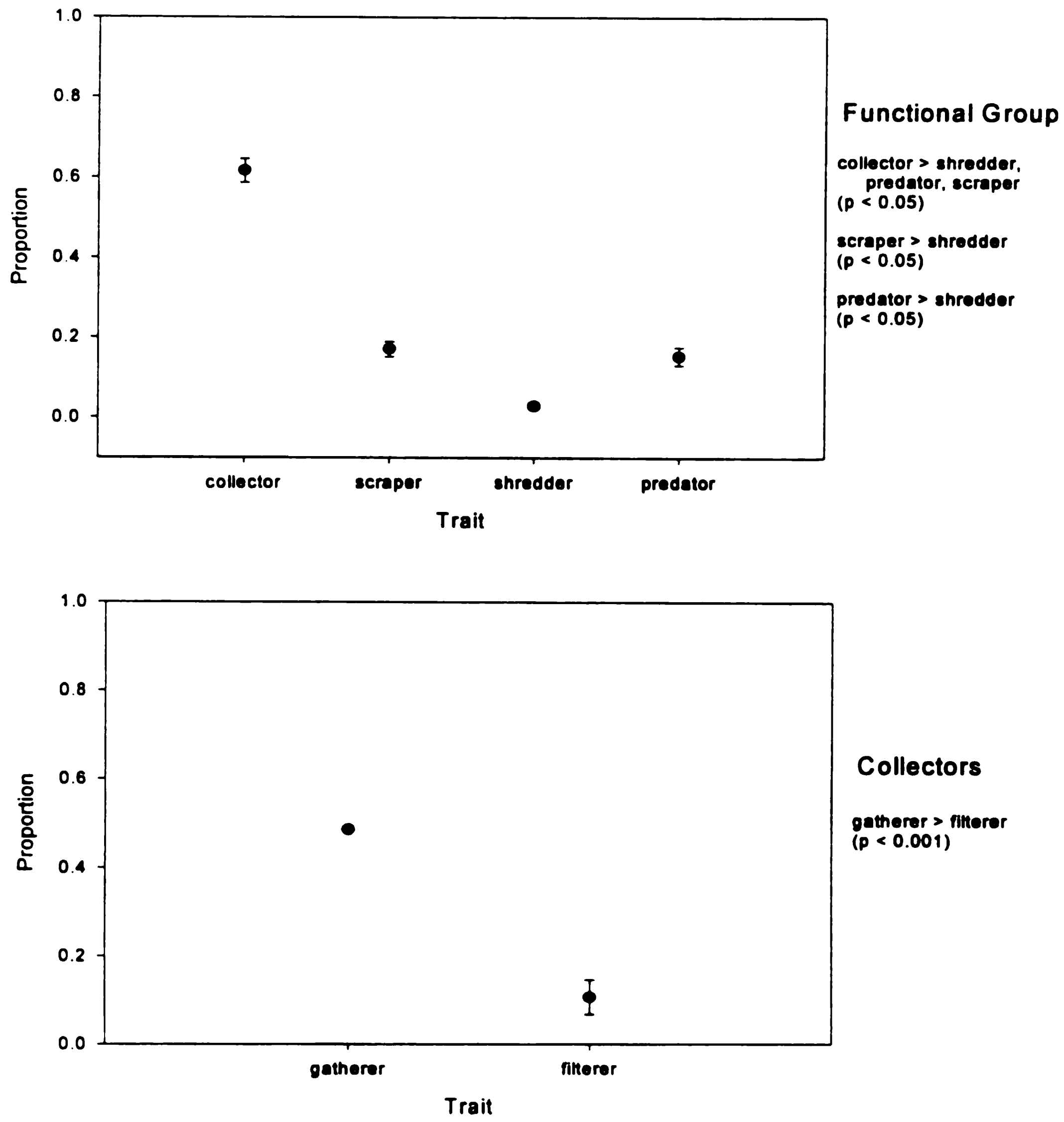


Figure 5-2a. One way analysis of variance results testing for differences in the abundance of macroinvertebrates in woody debris samples among functional categories. (Shown are means and S.E.) 2b. One way analysis of variance results testing for differences in the abundance of macroinvertebrates in woody debris samples among colector categories. (Shown are means and S.E.)

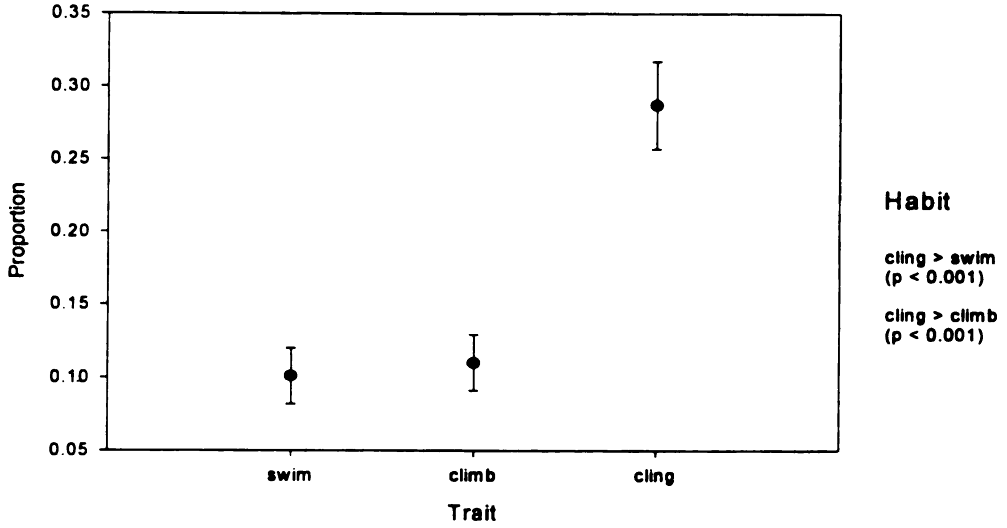


Figure 5-3a. One way analysis of variance results testing for differences in the abundance of macroinvertebrates in woody debris samples among locomotor behavior types. (Shown are means and S.E.).

Appendix 5-1. Taxa closely associated with CWD (wood-associated = wood-assoc; wood-dominant = wood-dom) and those that are not found in CWD samples (wood-absent= wood-abs; wood-averse = wood-av). Categories are described in the text. Trophic relationships (collector - (gatherer or filterer), scraper, predator, shredder), habit (clinging, climbing, swimming, sprawling, burrowing, planktonic), and dominant habitat (erosional/depositional; erosional or depositional) also are listed. (. = data missing)

Taxa	Type	Class	Order	Family	Trophic Relations	Habit	Habitat
Leptohyphes	wood-assoc	Insecta	Ephemeroptera	Tricorythodae	col-gath	cling	lotic
Aeshna	wood-assoc	Insecta	Odonata	Aeshnidae	pred	climb	lentic
Agrion	wood-assoc	Insecta	Odonata	Coenagrionidae	pred	climb	both
Paragnetina	wood-assoc	Insecta	Plecoptera	Perlidae	pred	cling	lotic
Gelastocoris	wood-assoc	Insecta	Hemiptera	Gelastocoridae	pred	sprawl	lentic
Lethocerus	wood-assoc	Insecta	Hemiptera	Belostomatidae	pred	climb; swim	both
Plea	wood-assoc	Insecta	Hemiptera	Pleidae	pred	swim; climb	lentic
Brachycentrus	wood-assoc	Insecta	Trichoptera	Brachycentridae	col-filt; scrap	cling	lotic
Limnephilus	wood-assoc	Insecta	Trichoptera	Limnephilidae	shred; col-gath	climb;cling sprawl;	both
Lype	wood-assoc	Insecta	Trichoptera	Psychomyiidae	scrap	cling	lotic
Nyctiophylax	wood-assoc	Insecta	Trichoptera	Polycentropodidae	pred; col-filt	cling	lotic
Platycentropus	wood-assoc	Insecta	Trichoptera	Polycentropodidae	shred	climb	both

Appendix 5-1 (continued)

Pycnopsyche	wood-assoc	Insecta	Trichoptera	Limnephilidae	shred; scrap	sprawl; climb	both
Carabidae	wood-assoc	Insecta	Coleoptera	Carabidae	pred		
Deronectes	wood-assoc	Insecta	Coleoptera	Dytiscidae	pred	swim; climb	both
Hydrochus	wood-assoc	Insecta	Coleoptera	Hydrophilidae	shred	climb	both
Hygrotus	wood-assoc	Insecta	Coleoptera	Dytiscidae	pred	swim; climb	both
Laccophilus	wood-assoc	Insecta	Coleoptera	Hydrophilidae	pred	climb; swim; dive	both
Brillia	wood-assoc	Insecta	Diptera	Chironomidae	shred; col-gath	burrow; sprawl	lotic
Caloparyphus	wood-assoc	Insecta	Diptera	Stratiomyiidae	col-gath	sprawl; swim	both
Micropsectra	wood-assoc	Insecta	Diptera	Chironomidae	col-gath	climb; sprawl	lentic
Paratendipes	wood-assoc	Insecta	Diptera	Chironomidae	col-gath	burrow	lotic
Nematoda	wood-assoc	Nematoda			macrop. pierc; pred	burrow; swim	both
Ancyronyx	wood_dom	Insecta	Coleoptera	Elmidae	col; scrap	cling	lotic
Anopheles	wood_dom	Insecta	Diptera	Culicidae	col-filt	planktonic	both
Belostoma	wood_dom	Insecta	Hemiptera	Belostomatidae	pred	climb	both
Boyeria	wood_dom	Insecta	Odonata	Aeshnidae	pred	climb	lotic

Appendix 5-1 (continued)

Cyphon	wood_dom	Insecta	Coleoptera	Helodidae	.	climb	lentic
Enallagma	wood_dom	Insecta	Odonata	Coenagrionidae	pred	climb	both
Glyptotendipes	wood_dom	Insecta	Diptera	Chironomidae	shred; col-filt; col-gath	burrow; cling	both
Hydraena	wood_dom	Insecta	Coleoptera	Hydraenidae	pred	cling; climb	both
Matus	wood_dom	Insecta	Coleoptera	Dytiscidae	pred	swim; dive	both
Niadidae	wood_dom	Oligochaeta	Haplotaxida		col	burrow	both
Paraponyx	wood_dom	Insecta	Lepidoptera	Pyralidae	shred	climb; swim	lentic
Cryptochironomus	wood_av	Insecta	Diptera	Chironomidae	pred	sprawl; burrow	both
Phaenopsectra	wood_av	Insecta	Diptera	Chironomidae	col-gath; scrap	cling	lentic
Stempellinella	wood_av	Insecta	Diptera	Chironomidae	.	sprawl	both
Stictochironomus	wood_av	Insecta	Diptera	Chironomidae	col-gath; shred	burrow	loyib
Cordulegaster	wood_abs	Insecta	Odonata	Cordulegastridae	pred	burrow	lotic
Plathemis	wood_abs	Insecta	Odonata	Libellulidae	pred	sprawl	lentic
Allocapnia	wood_abs	Insecta	Plecoptera	Capniidae	shred	cling	lentic
Helicopsyche	wood_abs	Insecta	Trichoptera	Helicopsychidae	scrape	cling	both
Rhagovelia	wood_abs	Insecta	Hemiptera	Veliidae	pred	skate	lotic

Appendix 5-1 (continued)

Molanna	wood_abs	Insecta	Trichoptera	Molannidae	scrape; pred; col-gath	sprawl; cling	both
Oecetis	wood_abs	Insecta	Trichoptera	Leptoceridae	pred; shred	cling; sprawl; climb	both
Agabus	wood_abs	Insecta	Coleoptera	Dytiscidae	pred	swim; dive	both
Bagous	wood_abs	Insecta	Coleoptera	Curculionidae	shred	sprawl; cling	lentic
Berosus	wood_abs	Insecta	Coleoptera	Hydrophilidae	macrop pierc;shred col-gath;	swim; dive	both
Neoheterocerus	wood_abs	Insecta	Coleoptera	Heteroceridae	.	.	.
Atherix	wood_abs	Insecta	Diptera	Athericidae	pred	sprawl	lotic
Cladotanytarsus	wood_abs	Insecta	Diptera	Chironomidae	col-gath; col-filt	burrow	both
Endochironomus	wood_abs	Insecta	Diptera	Chironomidae	col-gath; shred; col-filt	cling	lentic
Muscidae	wood_abs	Insecta	Diptera	Muscidae	pred	sprawl	both
Nilothauma	wood_abs	Insecta	Diptera	Chironomidae	col	burrow	lotic
Ectoprocta	wood_abs	Ectoprocta	.	.	col	cling	
Glossiphoniidae	wood_abs	Hirudinea	Rhynchobdellida	Glossiphoniidae	pred	swim	both
Unionidae	wood_abs	Pelecypoda	.	Unionidae	col-filt	burrow	both

Appendix 5-2. Total number of taxa found at a site, in non-woody debris habitats, and in woody debris habitats, and the number of unique taxa occurring only in wood habitats.

SAGCODE	Total Taxa	Non-Wood	Wood	Unique Wood
51	32	4	29	25
52	32	32	0	0
53	38	18	31	13
91	28	15	19	4
92	47	28	30	2
93	41	26	29	3
232	35	8	30	22
233	38	39	26	
234	46	46	0	
242	60	37	31	
243	41	41	1	
244	44	24	34	10
311	39	32	16	
312	43	23	29	6
313	37	37	0	
321	38	24	29	5
322	25	5	22	17
323	17	5	14	9
351	28	9	21	12
352	28	12	21	9
353	22	16	7	
361	51	26	41	15
362	43	26	29	3
363	49	31	35	4
375	49	33	29	
376	57	43	37	
377	44	32	33	1
2411	41	13	35	22
2412	42	18	32	14
2413	43	10	38	28
5111	54	34	37	3
5112	39	33	15	
5113	38	31	9	
5121	45	24	33	9
5122	33	10	28	18
5123	31	31	0	

CONCLUSIONS

The Saginaw Basin in central Michigan is structurally diverse with respect to its underlying Quaternary geology and land use. Soil productivity has been one of the major factors influencing current land use and land cover patterns in this region, resulting in a cascade of effects that have had a profound influence on both the structure and function of stream ecosystems. Huge expanses of wetlands located on the historic lake bed sediments were drained and placed under intensive agricultural production. Land management practices including channelization and riparian vegetation conversion to grasses have led to a simplified channel structure that poorly retains nutrients, sediments, and coarse woody debris. Abandoned farmland in areas with low soil productivity has slowly succeeded to old fields with savannah-like vegetation (now called range land). Stream channels in these regions have slow regained habitat heterogeneity as riparian vegetation invades the channels. Remnant second growth forest patches currently are concentrated in regions of unproductive, sandy soils that are unsuited for farming, but which have recently become attractive sites for low density residential development. Hydrologic patterns controlled by the underlying geology-- groundwater infiltration on morainal landforms and surface water phenomenon on lacustrine soils, interact with (and exacerbate) the negative effects of land management practices. Tile drainage in conjunction with wetland draining, and stream channelization result in flashy flow regimes that transport CWD out of the reach, and have erosive effects on the channel. Removing woody riparian vegetation and plowing to the edge of the stream bank results in increased sediment flow, and chemical inputs, and decreased inputs of coarse woody debris to the stream. Deciphering the effects of these complex interactions on the stream ecosystem would not have been possible without two sets of tools, geographic information systems and multivariate statistical techniques, and the widespread availability of spatial databases describing elevation, land cover, and hydrography in the region. When used in conjunction with field data, these tools have allowed me to quantify patterns of association and infer the effects of a variety of local and regional factors on stream ecosystems, particularly with reference to the standing stocks and distribution of coarse woody debris.

A combination of field-collected data, quantifying in-stream and riparian conditions across 12 catchments in the Saginaw Basin, and spatial data, quantifying the location and type of land use and Quaternary geology, were used to quantify the standing stocks and distribution of in-stream coarse woody debris. The long disturbance history of the region is reflected in modern-day standing stocks of CWD, which, along with the size of the logs, were much smaller in comparison to most other streams studied, especially those in high gradient, forested ecosystems (Table 2-12). Land use and surficial geology, by themselves, did not have an effect on most measures of wood abundance or size; however, interactions between land use and geology were evident with respect to their effects of the abundance of CWD and the density of debris accumulations. Highest standing stocks were found in association with Lac/Ag and Mor/Mix catchments, compared to catchments dominated by Lac/Mix and Mor/Ag land use and geologies.

At the channel scale the factors that appeared to have the greatest influence over CWD were the channel bank-full width and the percent of open canopy (Table 2-11). These two local-scale characteristics of the stream were the best predictors of the number and distribution of debris accumulations. Bank-full width was positively correlated with number of debris accumulations per 100 m and the $\sum$ accum size metric (reflecting the extent of channel covered by debris accumulations). Percent of open canopy was negatively correlated with those two CWD measures. Whereas many other studies (reviewed by Harmon, et al. 1986, Gurnell, et al. 1995) have found strong interactions between CWD and channel morphology, there did not appear to be any measurable effect of CWD on channel features such as the bank-full width or depth and extent or depth of pools and riffles.

Riparian vegetation and riparian width are determined by an individual landowner's preference in agricultural settings. As a result, factors influencing the absence of wood at a site are more difficult to predict than those influencing the presence of CWD. From a management perspective, the presence of woody vegetation in the riparian zone is more important than the width of the riparian zone in predicting CWD standing stocks, suggesting that landowner education may be instrumental in helping to restore riparian zone function. This speaks only to the role of the riparian zone in contributing CWD to the stream, however, and does not consider the role of herbaceous vegetation as a filter strip for sediments and anthropogenic chemicals.

Landscape features, including urban land use, link number, the S.D. elevation, and percent coarse till + sand/gravel were the best predictors of CWD density and debris accumulation density and distribution (Table 2-11). These landscape-scale predictors underscored the role of hydrology in the retention of CWD in the stream channel, and indirectly pointed to the negative influence of agricultural land use, especially on morainal landforms (Tables 2-14, 2-15). When predicting the actual volume (excluding volume = 0) of CWD, even small amounts of wetlands in a catchment had an effect on the regional stability of flow, which was instrumental in retaining CWD in the channel once it is delivered to the stream. Relatively rare land use types such as urban areas and wetlands were surprisingly influential as predictors of CWD abundance and distribution, and probably reflected the absence of agricultural land use more than anything else. The combination of local and landscape variables that best predicted debris accumulation density and distribution highlighted the interaction between channel-scale factors that influenced the entrainment of wood into a debris dam, and the landscape-scale factors that influenced retention.

When the composition of debris accumulations are broadly defined, their density was greater than that reported in other studies (Table 3-8). When only 'log/snag' accumulation types are considered, density were similar to those of forested streams. There is reason to believe that debris dams composed of logs and snags are smaller in the Saginaw Basin than elsewhere; however, standard methods for quantifying debris accumulation size are lacking, making direct comparisons difficult.

In these highly disturbed streams, the most prevalent structural element in the stream channel across the 49 sites was overhanging vegetation and root wads without trapped debris. The majority of debris accumulations were associated with the bank, rather than other types of obstructions such as root wads, point bars or islands, and there were surprisingly large numbers of debris accumulations for which no visible obstruction could be identified. These debris accumulations represent a pool of relatively mobile CWD and coarse particulate organic matter (CPOM) in the channel.

The debris accumulation types exhibited different responses to the landscape and local-scale predictors; 'log/snag' and 'loose log' accumulations were well explained by the landscape and local variables, whereas, 'root wad' and 'overhanging vegetation' types were not well explained at all. 'Log/snag' accumulations were best explained by factors such as (low) stream density and (low) flood height, higher topographic relief, larger bank-full widths and larger catchment areas (Figure 3-6). 'Loose log' accumulations were best explained by (large) bank-full width and catchment areas, and lower proportions of lacustrine sand soils. These results parallel those obtained for total number of debris accumulations and the $\sum$ accum size, and again reflect the influence of landform on hydrologic processes (e.g., flood height). No effect on channel features, such as pool frequency and depth, were observed when debris dam type were examined separately.

Perhaps the most important conclusion of this dissertation is that *the influence of landform cannot be ignored when attempting to understand the linkage between terrestrial and aquatic ecosystems.* Although land use and land cover are important and their effects appear to be unambiguous, this study and others (Richards, et al. 1996, 1997; Wiley, et al. 1997) demonstrate that land use effects are mediated by their underlying landforms and the influence of landform on the hydrologic regime.

Some of the mechanisms regulating CWD retention and export from a stream reach were examined by tracking tagged logs at two time periods separated by a winter/spring season and a flood with a return interval of about 5 years. In terms of absolute numbers of logs, the turnover was very large; more than 50% of the logs at a given location were exported and replaced from the fall through the following June following a flood with a 5-year return interval (Table 4-1). The proportion of retained log volume after the flood was two times greater than the recruited volume, while the proportion of individual logs retained was less than the proportion of recruited logs. This suggests that larger volume logs were retained, while smaller, more mobile logs were recruited.

High flood height was negatively correlated with the probably of retention, and positively correlated with recruitment (Figure 4-1); bank-full width had a similar response (Figure 4-2). Neither the original orientation, location of the log in the channel, nor a log's association with a debris accumulation influenced whether or not a log was retained. Nor could the distance that a log moved be predicted from either flow or channel characteristics, possibly because the retention and movement patterns of logs with branches differs from logs with a simple geometry.

Bank-full width is a good predictors of debris accumulation density, and specifically of 'log/snag' debris accumulation densities. In addition, low flood height was one of the factors explaining the abundance of 'log/snag' accumulations (Figure 3-5). These are relatively easy metrics to acquire in the field, and can potentially provide important information about CWD mobility as well as the density of CWD accumulations.

Due to the small standing stocks and sizes of logs (and debris accumulations) in the Saginaw streams, CWD does not play an important role in structuring the stream channel, although it is proported to play many different roles in forest stream ecosystems (Table 2-1). This leaves open the question: does CWD play a role in structuring the macroinvertebrate community, and if so, how? Despite low standing stocks of CWD across the basin, this habitat type supported 87% of the total macroinvertebrate taxa found; of those, 25 % were found only on wood, or wood was their dominant habitat (>90% of individuals were found on wood compared to other habitats). The importance of this habitat in contributing to taxa richness is illustrated by the fact that at almost 50% of the sites, wood habitats contributed an average of 11 unique taxa to the taxa richness. The most abundant taxa (23% of the total individuals) found in association with wood were amphipods and a chironomid. The other two dominants were the mayfly *Caenis*, and the elmid beetle, *Dubiraphia*. The functional and behavioral attributes of the community were diverse, suggesting that CWD serves as a hard substrate habitat whose community composition probably varies with the flow regime in which the wood is located.

Overall, coarse woody debris is not abundant across this region, and the factors that control the abundance are complex. At the landscape scale, both landform and land use are important predictors of CWD, but interactions between landform and land use result in complex patterns of association that are difficult to interpret. Factors that influence the hydrologic regime are particularly important for explaining the patterns of abundance and distribution of CWD. Relatively rare land use types such as urban areas and wetlands are surprisingly influential as predictors of CWD abundance and distribution. Channel width and riparian vegetation types are among the most important predictors of CWD at the local and riparian scale. Channel width also is an important predictor of CWD retention, along with flood height. Lastly, the role of CWD in this region is confined to biological, rather than physical effects. Geographic information systems and multivariate statistical techniques are indispensable tools for unraveling complex patterns across ecosystems.

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