DYNAMICS OF SEDIMENT AND WOODY DEBRIS IN HEADWATER STREAMS, SOUTHEAST ALASKA

by

TAKASHI GOMI
Bachelor of Agriculture, Hokkaido University, Japan, 1992
Master of Agriculture, Hokkaido University, 1994

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE STUDIES
(Department of Forest Resources Management)
FACULTY OF FORESTRY

We accepted this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA
December 2001

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Forest Resources Management

The University of British Columbia
Vancouver, Canada

Date April. 8, 2002.

DE-6 (2/88)

ABSTRACT

Headwater streams are the most important sources of water, sediment, nutrients, and organic matter for downstream systems. Timber harvesting and mass movement alter hydrologic, geomorphic and biological processes in stream channels and riparian zones of headwater systems. In particular, changes in abundance of woody debris and sediment related to timber harvesting and mass movement and the recovery processes for such disturbances affect the material dynamics and habitat conditions. Therefore, the amount and distribution of sediment and woody debris as well as bedload and suspended sediment transport for different management and disturbance regimes were examined in headwater streams of southeast Alaska. External influences (mass movement and timber harvesting) modified channel morphology and sediment transport from undisturbed old-growth conditions in different ways. In recent clear-cut channels, inputs of logging slash significantly increased the abundance of in-channel woody debris. In the absence of landslides and debris flows, woody materials remained in the channels 50 years after logging where young-growth confers (logged in 1950's) dominated the riparian zone. Woody debris related to logging activates initially stored sediment, created channel steps, and reduced sediment movement. When landslides and debris flows in 1962 (7 years after logging), woody debris pieces were transported from upper reaches of headwater streams and deposited in downstream reaches in recent landslide channels and in channels with young alder riparian stands. Because of the high sediment production from bank slopes, more bedload and suspended sediment was transported in recent landslide and debris flow channels. Once red alder actively re-colonized riparian zones 20 to 50 years after mass movement and then recruited woody debris and organic matter, greater amounts of woody debris and sediment storage behind woody debris were observed. The recovery processes related to vegetation regeneration on disturbed soil and woody debris recruitment into channels significantly decreased sediment transport. Temporal and spatial variations of availability of sediment and woody debris characterize processes and morphology in headwater streams. Such spatial and temporal variations in headwater systems are important for understanding organic and inorganic material dynamics through channel networks and evaluating the influence of timber harvesting on downstream ecosystems.

Key words: *woody debris; sediment movement; timber harvesting; headwater streams; southeast Alaska*

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

Chapter 4

Chapter 5

Conclusion

ACKNOWLEDGEMENTS

I am most gratefully to my supervisor Roy C. Sidle for providing continuous encouragement and enthusiastic support during the years of fieldwork and thesis writing. I also owe Roy many thanks for introducing me excellent field and colleagues in southeast Alaska, for his willingness to discuss almost anytime, for his patience to fill the preliminary drafts of manuscripts with red ink, and for his financial support without which I have never survived. I also thank Roy and his wife, Karin, for letting me stay in their home when I studied in the National University of Singapore for four months.

I would like to thank my supervisory committees: John Richardson, Olav Slaymaker, Mason Bryant and Richard Woodsmith for critical comments and insightful discussion to develop this thesis. Without their guide throughout this project, I cannot accomplish for conducting fieldwork and developing this thesis. Particularly, John always encouraged me for further studies after Roy left from UBC. I also would like to thank Mike Bovis, Amod Dhakal, Brian Frennete, Marwan Hassan, Dan Hogan, Adelaide Johnson, Karin Laursen, David Luzi, Dave Montgomery, Dan Moore, Futoshi Nakamura, and Douglas Swanston for their critical and insightful comments.

I am greatly thankful to Mason Bryant and Richard Woodsmith, USDA Forest Service, Pacific Northwest Research Station, for continues discussions of this project and their supports of the fieldwork in southeast Alaska. I also extend my thanks to Brenda Wright, Bryan Davis, Frances Bile, and Patricia Krosse, USDA Forest Service, for providing their kind support and very useful information. I am also gratefully to field crews in Hollis for their friendships and helpful supports of fieldwork in steep headwater channels: Russell Smith, Brittany Graham, Adam Herren, Heather Hodgm, Karen McCartney, Katherine McGee, Dave Allan, Allison Cooney, Junjiro Negishi, Jeff Hogland, Robert Walton, Dino Gnoato and Yuho Okada. Ressull helped me the hardest stream surveys in 1998. Dino and Yuho did excellent and the most painful jobs for constructing four weirs with acceptable 5 to 10 % leakage for ten days (before started storm season!) in 1999. Jeff and I spent a night in cold and stormy rain because we lost in wood. Yuho and I almost slide on avalanche trucks in the spring 2000. I also extended my appreciation for their friendships and supports: Jack Piccolo and his wife Eva, Scott Alexander, Duke Busch, Shully Millstein, Osvaldo Hernandez and other staffs in Forestry Sciences Laboratory, Juneau. I had wonderful and unforgettable moments with you in southeast Alaska.

Finally, my deepest thanks go to my parents, sister, and brother for their support during this study.

Introduction

Introduction

Ever since James Hutton presented a uniformitarian interpretation of landform evolution in his comprehensive dissertation "*Theory of the Earth*" (1795), geomorphologists and hydrologists have puzzled over the dynamic processes of the earth at various temporal and spatial scales. One of the most fundamental aims in the shared histories of geomorphology and hydrology is to understand the patterns and processes of material transport throughout river and stream systems (Wolman and Miller, 1960). Hydrologic and geomorphic processes can function at different temporal and spatial scales but are interdependent (Schumm and Lichty, 1965). Further, processes operating at large scales may control functions at smaller scales (Frissell et al., 1986). In particular, hydrologic and geomorphic processes in forested headwater streams are governed by attributes that may exhibit a wide range of temporal responses. For instance, types of landforms, which develop during a 1000 to 10,000 year period, set the physical template for the occurrence of mass movement such as landslides and debris flows (Swanson et al., 1988). Landslides and debris flows with recurrence intervals ranging from 100 to 1000 years alter the availability of sediment as well as channel morphology (Benda and Dunne, 1997). Additionally, the availability of sediment modifies the amount and regimes of bedload and suspended sediment transport in the timeframe of 10 to 100 years (Grant and Wolff, 1991). Similarly, woody debris, pieces of dead wood and branches, in streams alter fluvial processes over a period of 10 to 100 years (Harmon et al., 1986). Such hydrologic and geomorphic processes set templates of biological processes in and around streams (e.g., Hack and Goodlett, 1960; Hynes, 1975).

For the last two decades, the role of woody debris in altering channel morphology and sediment transport in forested streams has been recognized (e.g., Harmon et al., 1986; Woodsmith and Swanson; 1997). Both episodic and chronic (regular and cyclical) movements of woody debris and sediment modify geomorphic conditions in headwater streams. For instance, recruitment and movement of woody debris alters the morphological complexity (e.g., channel steps and pools) of headwater streams (Montgomery et al., 1996). Woody debris pieces and jams store sediment and organic matter (Bilby and Likens, 1980) and alter substrate composition and aquatic habitat for fish and macroinvertebrates (Wallace et al., 1995). The presence of woody debris pieces and jams can alter the distribution of alluvial deposits and bedrock reaches in mountain streams (Montgomery et al., 1996). Landslides and debris flows can potentially transport large amounts of woody debris and sediment in addition to modifying channel morphology (Benda, 1990).

Timber harvesting may affect the dynamics of material transport in forested headwater systems (Slaymaker, 2000). The recruitment of woody debris decreases for 50 to 100 years because of the removal of riparian vegetation (Ralph et al., 1994). Logging residue (or slash) that is recruited during and after timber harvesting modifies channel morphology and sediment movement (Froehlich, 1973). Vegetation removal, logging roads, and culvert installations alter hydrologic regime and sediment transport. The probability of landslides and debris flows increases 3 to 15 years after logging due to decreasing root strength (Sidle et al., 1985). More sediment is typically available in such disturbed areas until vegetation recovers (Grant and Wolff, 1991).

The interactions between woody debris and sediment are key to understanding the influence of management and disturbance regimes on the physical and biological processes in headwater streams. However, few studies have examined the influence of management and disturbance regimes on the geomorphic attributes and physical dynamics of headwater streams. Both episodic and chronic movements of sediment and woody debris must be studied in order to understand the dynamics of headwater streams and their connectivity to downstream reaches. Moreover, understanding the roles and processes of headwater streams are important for establishing better principles for watershed management. The research presented in this thesis was conducted to achieve a better understanding of woody debris and sediment dynamics related to the occurrence of mass movement and timber harvesting in steep headwater streams. As well, this study considers recovery processes after mass movement and timber harvesting (Figure I.1).

This research focused on streams affected by timber harvesting and mass movement in glaciated landscapes of steep forested terrain in North America. The streams are located in the Maybeso Experimental Forest and the adjacent Harris River basin, Prince of Wales Island, southeast Alaska. The five different regimes of timber harvesting and related mass movement are: old-growth (OG); recent (3 year old) clear-cut (CC); young-growth (37 years after clear-cutting) conifer forest (YC); young-growth (40 years after clear-cutting and landslides in 1960) alder riparian forest (YA); and recent landslide and debris flow channels (LS). Biogeoclimatic controls (e.g., vegetation, precipitation, glaciation, and geology) on these headwater streams are representative of steep glaciated forest landscapes in southeast Alaska.

Structure of this thesis

The findings of this investigation are organized into five chapters (Figure I.1). Each chapter details processes and attributes at different spatial and temporal scales. Although the approaches that are taken in the five chapters differ, findings of each chapter are interlinked in the context of scales because each chapter is nested within the previous chapter(s), except Chapter 5 (Figure I.2). The relative temporal and spatial scales of geomorphic processes progressively decline from Chapter 1 to 4. Chapter 5 emphasizes sediment and woody debris movement within the context of linkages between hydrologic and geomorphic processes at larger spatial and temporal scales. The objective of Chapter 1 is to highlight the functional roles of headwater systems and their linkages with downstream systems. In this chapter, the uniqueness of hydrologic, geomorphic, and biological linkages in small headwaters systems is contrasted with those in larger watersheds (network systems). Linkages within headwater systems and between headwaters and downstream reaches are important aspects in understanding the material dynamics for, not only headwater streams, but throughout the channel network (Figure I.2). The purpose of Chapter 2 is to determine whether the amount, distribution, and accumulation of woody debris and sediment is altered by timber harvesting and related mass movement and whether a relationships exists between woody debris and sediment storage. Chapter 3 addresses the smaller-scale issue of whether the amount and type of woody debris (influenced by management and disturbance regimes) alters the morphology of headwater channels. In particular, the differences in channel steps and reach morphology related to management and disturbance regimes are assessed. Chapter 4 examines the small-scale dynamics of sediment (bedload and suspended sediment) and woody debris based on information obtained during the 1999 storm season. The focus of Chapter 5 is on the larger temporal and spatial variations of sediment and woody debris movement during mass movement and more regular (chronic) events. The long-term consequences of hydrologic and geomorphic linkages in sediment and woody debris dynamics within headwater streams and from headwater to downstream systems are discussed (Figure I.2). Finally, an overview of the effects of timber harvesting and related mass movements on the dynamics of woody debris and sediment is presented in the concluding chapter (Figure I.1). This description examines the potential scenarios of woody debris and sediment movement from source, input, storage, and output during episodic and chronic events.

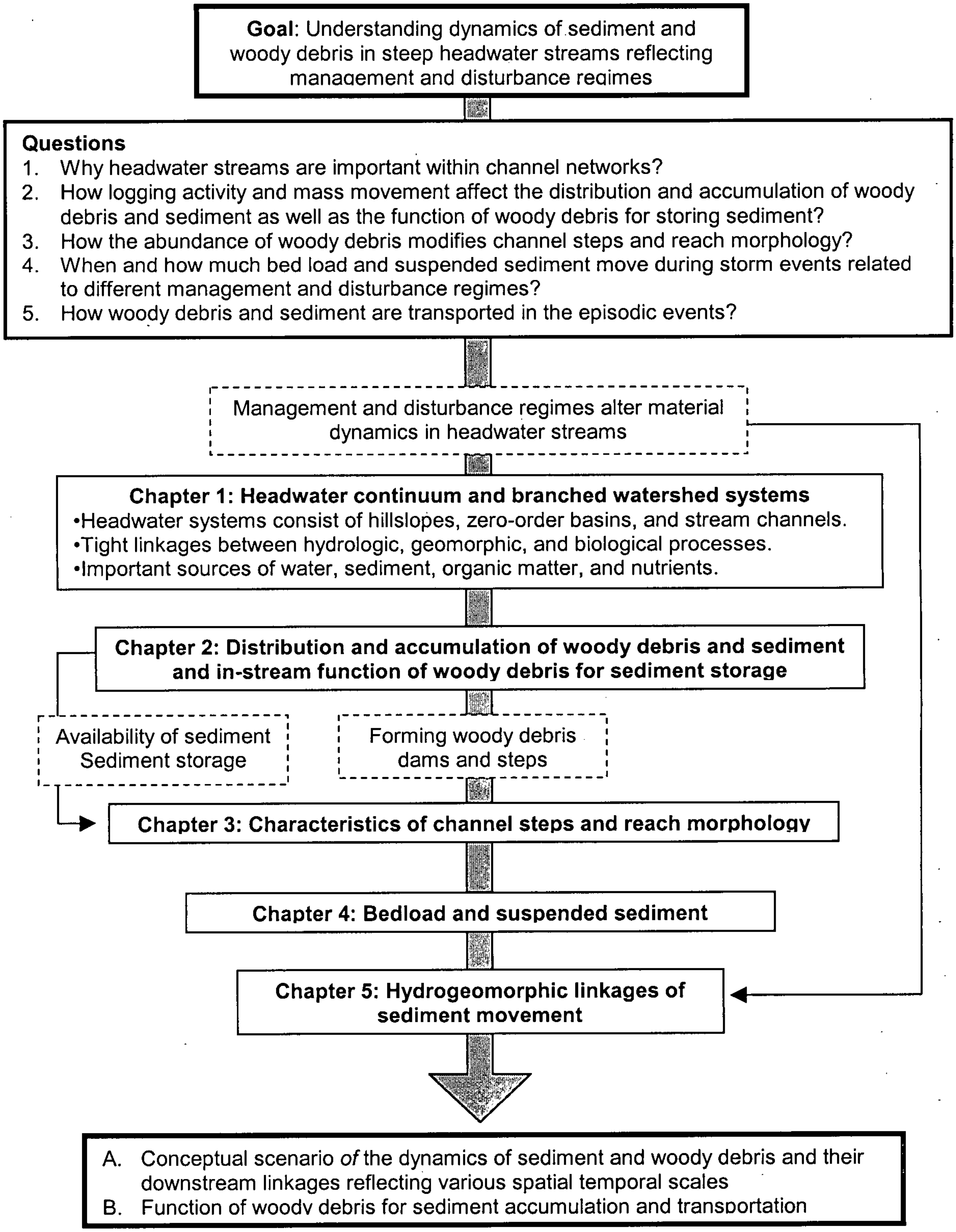


Figure I.1 Flow chart illustrating the thesis structure

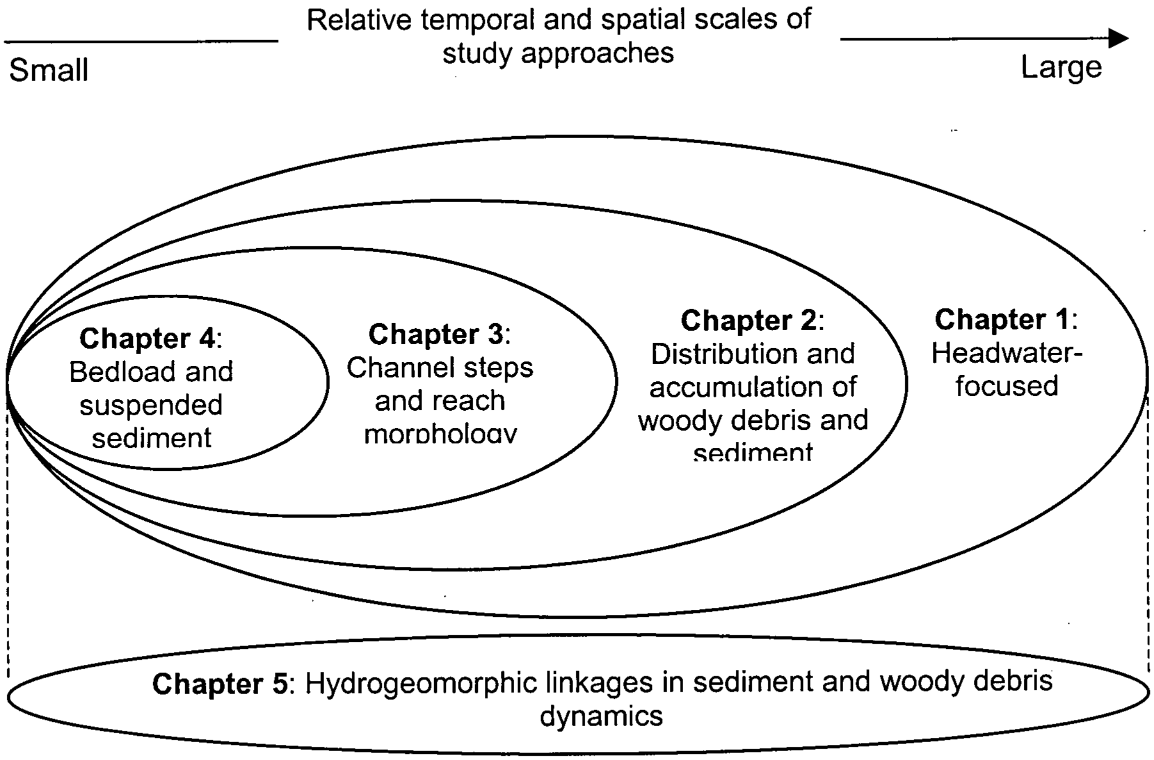


Figure I.2 Temporal and spatial structure of the thesis

Chapter 1

Headwater and network systems

-Understanding processes and downstream linkages of headwater streams-

1.1. Introduction

Headwater systems are the headmost area within a channel network and are characterized by tight linkages among hydrologic, geomorphic, and biological processes from hillslopes to stream channels and from terrestrial to aquatic environments (Figure 1.1 and 1.2) (e.g., Hack and Goodlett 1960). Sediments and woody debris from episodic landslides and debris flows directly interact with headwater channels in mountainous regions (Dietrich and Dunne 1978; Benda and Cundy 1990; Whiting and Bradley 1993). Both the zones of initiation and deposition of these mass movements often occur within headwater systems (Sidle et al. 1985). The processes of mass movement affect the accumulation and distribution of woody debris throughout the channel network. Channel reach types (e.g., cascades, steps, and pools) in headwater channels vary due to sediment supply, larger substrate, exposed bedrock, and woody debris (Montgomery and Buffington 1998; Halwas and Church 2002). Hydrologic processes in hillslopes and zero-order basins control streamflow generation (Tsukamoto et al. 1982; Sidle et al. 2000) and stream chemistry (Likens et al. 1977). The expansion and shrinkage of wetted areas and stream channels with changing antecedent precipitation conditions significantly modify subsurface flow paths (Hewlett and Hibbert 1967). Such changes affect landslide probability in hillslopes (Side et al. 1985) as well as organic matter and nutrient fluxes from terrestrial to aquatic environments (Dieterich and Anderson 1998).

Biological processes in headwater systems respond to the complex interactions of geomorphic and hydrologic processes at various temporal and spatial scales (Hynes 1975; Meyer and Wallace 2001). Leaf litter and woody debris from riparian stands (allochthonous input) and hillslopes (lateral input) are important sources of food and habitat for biota in small streams (Richardson 1992; Wallace et al. 1999). Relatively large substrate and woody debris in headwater channels modify channel hydraulics and provide sediment storage sites (Zimmerman and Church 2001); this in turn alters habitat types and accumulation of organic matter (Webster et al. 1999). Stream and stormflow generation processes modify organic matter dynamics (Kiffney et al. 2000) as well as biological community structure and life cycles of aquatic fauna in headwater channels (e.g., Dieterich and Anderson 2000).

Because the spatial extent of headwater systems comprises a major portion (70 to 80 %) of the total catchment area (Sidle et al. 2000; Meyer and Wallace 2001), headwater systems are important sources of sediment, water, nutrients, and organic matter for downstream systems. Sediment produced in headwater systems moves through channel networks and alters channel morphology (Hogan et al. 1995; Benda and Dunne 1997a, b). Floods induce scour and deposit sediment along channels, thus damaging riparian vegetation (Swanson et al. 1998). Sediment transported from headwater tributaries creates various channel environments (Nakamura et al. 2000) and modifies patterns of channel morphology, riparian structure, and hyporheic exchange (Gregory et al. 1991) as well as macroinvertebrate communities in downstream reaches (Rice et al. 2001). Greater percentages of allochthonous organic matter are transported from headwater tributaries (Cummins et al. 1983; Webster et al. 1999; Kiffney et al. 2000). Movement of detrital material and invertebrates from headwater reaches supports the downstream food web: this in turn alters productivity, population density, and community structure of stream biota in downstream reaches (Wipfli and Gregovich 2002).

Although hydrologic, geomorphic, and biological processes in headwater systems have been studied for the last 50 years and much knowledge related to these systems is available (e.g., Hack and Goodlett 1960; Hewlett and Hibbert 1967; Likens et al. 1977), the roles of headwater streams within the watershed and the linkages from headwater to downstream systems are poorly understood. Headwater systems are critical areas for nutrient dynamics and habitat of macroinvertebrates, fish, and amphibians within watersheds (Meyer and Wallace 2001). Because of their geographical isolation, headwater systems also support genetically isolated species: thus, they support an important biodiversity component in watersheds. For instance, new and endangered species are often found in headwater streams because such streams are relatively unexplored (e.g., Dietrich and Anderson 2000). Therefore, understanding the spatial and temporal variations of hydrologic, geomorphic, and biological processes in headwater systems is the key to comprehending diversity and heterogeneity of riparian and riverine ecosystems. Since headwater systems are intimately linked to downstream systems, the protection of headwater systems is also important for understanding and protecting downstream ecosystems. However, the roles of headwater systems are typically underestimated and inadequately managed compared to larger, downstream systems, because headwater streams are small and numerous. Management practices for protecting and restoring headwaters may need to consider them differently compared to larger systems because headwater systems have greater drainage density and different land use types and intensities. Consequently, inherent process differences between headwater systems and larger watersheds need to be recognized in both conceptual and field studies for understanding the roles and downstream linkages in headwater systems. Therefore, our objectives of this paper are: (1) to review characteristics and differences in processes between headwaters and larger watershed systems; and (2) to demonstrate spatial and temporal variations of hydrologic, geomorphic, biological processes in headwater systems and the linkages of headwaters to downstream systems.

Our primary focus is on steep (> 4° gradient channels) headwater systems in forested areas. Geomorphic time and space scales in this study are up to 1000 years and 100 km^2, respectively. Thus, the effects of glaciation, tectonics, volcanism, and Holocene climate change are not considered, although we acknowledge that landforms (e.g., glaciated U-shaped valleys) set the template for process rates in headwater systems.

1.2. Conceptual structures of stream ecosystems

1.2.1. Previous studies

Many conceptual studies have demonstrated the functional relationships of scales and processes in geomorphology, hydrology, and biology implicit to the understanding of stream ecosystems. Recognition of stream systems as a continuum was a major advance in developing a functional and dynamic perspective from up- to down-stream systems (Hynes 1975; Vannote et al. 1980). Understanding and organization of temporal and spatial scales and their causality have affected paradigms in modern science and landuse management. In geomorphology, Schumm and Lichty's (1965) comprehensive paper first demonstrated the dependent and independent processes of landform evolution at various temporal and spatial scales. Church and Mark (1980) discussed proportional characteristics of landforms and their behaviors at different scales.

The functional relationships among geomorphic processes in space and time are recognized as controls on the continuity of material transport in stream ecosystems. The equilibrium concept of geomorphology (Leopold et al. 1964), which demonstrated the relationship between sediment supply and transport led to the development of the geomorphic perspective of fluvial processes in a continuum from up- to down-stream reaches. For instance, Hey (1979) suggested that a process-response model with functional linkages from up- to down-streams was needed to explain and predict channel responses to a set of input conditions. Sediment budgets and routing were used to describe the spatial and temporal linkages of sediment movement along channels (Dietrich and Dunne 1978). Additionally, Wolman and Millar (1960) and Dunne (1991) demonstrated temporal and spatial linkages between hydrologic and geomorphic processes with respect to rainfall-landslide thresholds and channel network development. Benda and Dunne (1997a, b) examined the occurrence of mass movement in hillslopes and related sediment routing processes through a channel network from a stochastic viewpoint and concluded that continuity and discontinuity of sediment transport occurred within watersheds due to changes in valley width and channel gradient.

Continuity and discontinuity of biological processes from upper to lower reaches has been discussed in the context of heterogeneity of habitat, population, and community dynamics. The river continuum concept (Vannote et al. 1980) articulated upstream linkages and downstream adjustment of stream ecosystems based on changes in channel morphology through streams and rivers (Leopold et al. 1964). Based on the river continuum concept, Ward and Stanford (1983, 1995) developed a serial discontinuity concept where a dam or channel morphology (e.g., confined headwaters, meandering and braided reaches) disconnects the up- to down-stream continuum. Surface and subsurface flow interactions along channel corridors are important to nutrient cycling and biotic communities (Newbold et al. 1982; Stanford and Ward 1993). A hierarchical classification of stream ecosystems was proposed to examine continuity and discontinuity of impacts on stream biota at different scales within watersheds (Frissell et al. 1986). Patch dynamics, formed by micro-topographic attributes, may indicate the fragmentation of habitat and community structure in stream ecosystems (Pringle et al. 1988). Disturbances (e.g., landslides, debris flows, floods, and droughts) may control the patch distribution of organisms in and around stream systems (Townsend 1989; Gregory et al. 1991). Montgomery (1999) demonstrated that geomorphic processes set the templates of biological processes of disturbance, the river continuum, and patch dynamics in his process domain concept.

Although the importance of channel network structure for material dynamics has gradually been recognized (e.g., Johnson et al. 1995; Benda and Dunne 1997b; Meyer and Wallace 2001; Rice et al. 2001), most of the earlier conceptual and field studies have assumed linear relations of watershed processes and, thus, disregarded network structures such as tributary pattern, density, and junction effects. The river continuum concept (Vannote et al. 1980) evokes not a network (branching shape), but a linear concept from upper to lower stream reaches. Similarly, the nutrient spiraling concept (Newbold et al. 1982) presents a more complex, but still linear abstraction of solute dynamics in stream ecosystems within channels and hyporheic zones (Fisher 1997). However, Minshall et al. (1988) and Johnson et al. (1995) observed that landform attributes, such as tributary junctions in channel networks, affect the river continuum concept. Kirkby (1993) and Robinson et al. (1995) demonstrated the importance of channel networks in drainage basins for understanding and forecasting flow regimes, sediment transport processes, and landform evolution. Fisher (1997) noted that a paradigm shift from linear to network (branched shape) systems is necessary to understand the processes and linkages of physical and biological dynamics in stream ecosystems. Benda et al. (1997b) and Rice et al. (2001) emphasized the importance of channel network structure to understand the longitudinal variations in sediment movement and aquatic environments.

1.2.2. Headwater and network systems

Structural differences and the continuous-discontinuous nature of processes are critical for distinguishing hydrologic, geomorphic, and biological processes between headwaters and larger watershed systems. The watershed network can be partitioned into two systems based on characteristics of processes: (1) headwater and (2) network systems. Hydrologic, geomorphic, and biological processes in headwater systems are cascading from hillslopes to streams (Figure 1.3). Because hillslopes and streams are tightly coupled, material transport within headwater systems thus can be predicted as processes from hillslopes to stream channels. In contrast, material routing in larger watersheds is controlled by the channel network structure because numerous headwaters are nested within. Therefore, network structure must be considered in predicting material transport in larger watershed systems (Fisher 1997) (Figure 1.3). Nevertheless, processes from headwaters to downstream systems are often discontinuous because of changes in valley width, tributary junction angle, substrate size, and channel gradient (Benda and Cundy 1990; Ward and Stanford 1995; Bravard and Gilvear 1996; Rice et al. 2001).

Headwater systems contain four topographic units with distinctive biological and hydrological processes (Hack and Goodlett 1960): (1) hillslopes, (2) zero-order basins, (3) ephemeral or temporal channels emerging from zero-order basins, termed "transitional" channels, and (4) first- and second-order stream channels depending on linkages from hillslopes to channels (Figure 1.1). Hillslopes have either divergent or straight contour lines typically with no channelized flow. A zero-order basin is defined as an unchannelized hollow with convergent contour lines (e.g., Tsukamoto et al. 1982). Colluvial material from adjacent hillslopes typically fills such hollows. Although saturated overland flow may be observed in zero-order basins and at the foot of hillslopes during storm events, biological activity in such hillslopes and zero-order basins is terrestrial (Hack and Goodlett 1960). Channels with defined banks may emanate from zero-order basins (Tsukamoto et al. 1982); if channels exist at the outlet of these basins they represent the head-most definable channels with temporary or ephemeral flow. Temporary channels have more or less continuous flow at least 4 to 5 months in an average year, while ephemeral channels flow only for several days during periods of high antecedent moisture condition (Dieterich and Anderson 2000). Thus, temporary and ephemeral channels emanating from zero-order basins typically cannot support the complete life cycles of the juvenile stages of aquatic macroinvertebrates, except for those species with a long diapause stage or other strategies for tolerating absence of surface flow (e.g., Anderson 1997; Meyer and Wallace 2001). Despite the inability to support macroinvertebrates, such channels are integral parts of channel networks and have distinct roles (e.g., temporary storage of organic matter) (Dieterich and Anderson 1998, 2000; Halwas and Church 2002); thus, we call such streams "transitional first-order channels" or simply "transitional" channels (Figure 1.1). Transitional channels may gradually or abruptly begin from zero-order basins, depending on concentration (critical length) of saturated and Hortonian overland flow during storm events. Such channels may also contain discontinuous segments prior to entering first-order channels (Montgomery and Dietrich 1989). First-order streams are the uppermost channels with either perennial flow or sustained (more than 4 to 5 months during an average year) intermittent flow. First-order channels may directly emanate from the outlet of zero-order basins depending on flow generation mechanisms (e.g., springs and seeps). Second-order or even higher order streams may be considered headwater streams depending on degree of coupling between hillslopes and channels (e.g., transport distance of debris flow) that are discussed later in this paper. Both first- and second-order channels may have intermittent reaches (dry parts) depending on groundwater level and volume of alluvium.

1.2.3. Size of headwater systems

In the river continuum concept (Vannote et al. 1980), headwater streams were defined as first- to second-order channels based on Strahler's (1957) channel classification. However, potential problems of such classifications are: (1) stream orders depend on scales of maps; (2) stream orders are modified by basin-scale topography (e.g., steep mountains *versus* plains); and (3) stream orders are not suitable for explaining hydrologic, geomorphic, and biological processes as well as the importance of headwater streams. Meyer and Wallace (2001) noted that most detailed topographic maps did not include most headwater channels that might be found in field inventories. Thus, "headwaters" defined by Strahler's system and the river continuum concept pose ambiguities related to identification and interpretation of the sizes of headwater systems.

Processes from hillslopes to streams are important for defining the downstream limits of headwater systems. For instance, the transition from debris flow-dominated to alluvial-dominated processes occurred in headwater streams of Oregon for drainage areas up to 1.0 km^2 (Benda and Dunne 1987) (Figure 1.4). The major causes for the deposition of debris flows are decreasing channel gradient, abrupt tributary junction, and flow divergence (Benda and Cundy 1990). Swanson et al. (1998) also noted that drainage areas from 0.01 to 1km^2 (1-100 ha) are appropriate for distinguishing headwater streams based on physical and biological processes. Using digital elevation models, Montgomery and Foufoula-Georgiou (1993) demonstrated that a shift from colluvial to alluvial geomorphic processes occurred from 0.1 to 1.0 km^2. However, digital elevation models have limitations related to identifying headwater swales. With developments in laser altimetry, DEM's with contour intervals ≤ 2m can be developed – such precision will facilitate identification of geomorphic hollows and other features.

Variation of discharge in drainages less than 1 km^2 was greater than for drainages larger than 1 km^2 based on the representative elementary area (REA) concept (Figure 1.4; Woods et al. 1995). Wood et al. (1988) and Woods et al. (1995) noted that hydrologic processes within a 1 km^2 area are governed by hillslope processes related to soil depth, topography, rainfall intensity, and vegetation. Such site factors create greater variation of unit area discharge. In contrast, hydrological response in basins greater than 1 km^2 is more affected by routing processes and the structure and extent of the floodplain.

Based on the findings of such studies, the largest drainage area of headwater systems is likely 1km^2 (Figure 1.4). Although we suggest a relative upper size limit (1km^2) for headwater systems depending on the region, process-based criteria are more important to the definition of headwater systems than simply catchment area (Whiting and Bradley 1993; Montgomery 1999). In the following sections, we review hydrologic, geomorphic, and biological processes in headwaters (≤ 1 km^2 in drainage area) and network systems (> 1 km^2 in drainage area).

1.3. Hydrogeomorphic and biological processes

Different magnitudes and frequencies of hydrologic processes occur in headwaters and large watershed systems (Woods et al. 1995). Geomorphic processes in headwaters are largely stochastic, while more chronic processes related to routing of sediment, water, and wood are common in channel network systems (Benda and Dunne 1997a, b). Such different hydrogeomorphic processes between headwater and network systems also modify biological community structure and distribution as well as recovery processes of stream biota from disturbances (Rice et al. 2001).

1.3.1. Hydrogeomorphic processes

Headwater systems

Water inputs of headwater systems are unique compared to larger watershed systems. Because headwaters occupy the highest positions in catchments, precipitation and snow accumulation is generally greater in headwaters compared to lower elevation zones (Table 1.1). Variations of rainfall inputs among headwater systems are greater; thus, isolated precipitation is typically observed in headwater systems compared to the overall watershed. The relative temporal fluctuation of peak flows in headwaters is greater than in larger watersheds (Table 1.1; Figure 1.4) (Woods et al. 1995; Robinson et al. 1995). Water inputs strongly affect hillslope and channel conditions because of the close coupling of hydrologic and geomorphic processes within confined and steep valleys of headwater systems (Sidle et al. 2000) (Figure 1.1). Stream temperature and water chemistry in headwater channels is closely related to soil pore structure and bedrock fractures in hillslopes and zero-order basins (Likens et al. 1977). Subsurface discharge from hillslopes contributes baseflow and stormflow to headwater channels, initiates certain erosion processes, and is important for the development of headwater topography (Dunne 1991). Stormflow in headwaters responds rapidly to intense rainfall because of their relatively smaller storage capacity and shorter flow paths. Stormflow generation in headwater channels is also affected by the responses of hillslopes and zero-order basins to changing antecedent moisture conditions (Hewlett and Hibbert 1967; Sidle et al. 2000, Figure 1.5). Strom flow is primarily generated by direct runoff from saturated riparian areas and channel interception during lower antecedent moisture conditions. Throughflow from the soil matrix at the foot of hillslopes and riparian areas gradually increases with increasing wetness of the basins. During wet conditions, zero-order basins with relatively shallow soils start contributing surface runoff, and preferential flow from hillslopes augments stormflow. Zero-order basins and preferential flow paths are major contributors to stormflow during very wet conditions (Sidle et al. 2000). "Transitional" channels emerging from zero-order basins typically flow during such storms preceded by very wet conditions (Figure 1.5). During rain and rain-on-snow events, nearly saturated conditions in hydrologically responsive areas (e.g., zero-order basins) may induce slope failure (Sidle et al. 1985). During the dry seasons, however, intermittent (dry) reaches may be found in headwater channels depending on groundwater level and depth of alluvium.

Landslides and debris flows are dominant geomorphic processes in headwater systems (Table 1.1). Such mass movements transport sediment and woody debris from hillslopes to channels and modify stream and riparian conditions. Sediment and woody debris are routed as channelized debris flows and deposit in the downstream reaches of headwater systems (Benda and Cundy 1990). Exposed bedrock and less woody debris typify scour and runout zones (Gomi et al. 2001). In contrast, massive piles of woody debris and sediment are found in deposition zones of debris flows (Hogan et al. 1995). Log jams at the terminal end of debris flows often modify both longitudinal and planimetric (e.g., braiding, forming side channels) profiles of channels. Such geomorphic processes also alter riparian forest structure, for instance, alder (*Alnus* spp.) typically invades scour and deposition disturbance zones created by mass movement in the Pacific Northwest of US and Canada. Adjustment of channel morphology after landslides and debris flows largely depends on sediment and woody debris inputs. Regenerating riparian stands in scour and deposition zones of debris flows begin to restore the recruitment of woody debris 20 to 50 years after mass movement in headwater streams (Gomi et al. 2001).

Channel morphology in headwater systems can be characterized by channel obstructions such as large woody debris and boulders (Table 1.1) (Zimmerman and Church 2001). Channel depth in headwaters tends to be shallower relative to the average diameters of such channel bed obstructions. Because substrate materials are not well sorted, interlocking boulders and cobbles modify the stability of channels, formation of channel steps, and create sites for sediment storage (Zimmerman and Church 2001). Woody debris pieces also store sediment and modify channel roughness. Relatively smaller woody debris pieces and jams also have similar functions in headwater channels due to the narrow channel width (Gomi et al. 2001). The accumulation and distribution of woody debris alters the distribution of channel reach types such as cascade, step-pool, and bedrock (Montgomery and Buffington 1998; Halwas and Church 2002).

Network systems

Observations of single headwater systems cannot be simply extrapolated to network systems where contributions from upstream dominate base flow and stormflow generation. Because of the longer routing processes of water and greater storage capacity, peak flows in downstream reaches are often attenuated, lost partly to deep percolation and desynchronized flows that buffer peaks between headwaters and downstream locations. Floodplain and riparian zones also contribute to stormflow generation in larger watershed systems. Synchronized outflows from headwaters enhance peak flow in downstream reaches, while desynchronized outflows from headwaters attenuate flood peaks (Robinson et al. 1995; Ziemer and Lisle 1998, Table 1.1; Figure 1.6). Timing of outflows may be altered by hillslope and channel storage capacity (e.g., soil and substrate depth), amount of deep percolation from headwater systems, routing length, woody debris and other roughness elements in channels, and riparian vegetation characteristics.

More regular sediment transport, such as bedload movement, dominates sediment transport in downstream reaches (Table 1.1). Sediment delivery from headwater to downstream is often interrupted because sediment is temporarily stored in or along the streambed, banks, terraces, and debris fans (Hey 1979; Benda and Dunne 1997a; Nakamura et al. 2000). Number of sediment storage sites increases toward downstreams. Sediment transport from tributaries alters patterns in the downstream fining of substrate size (Rice et al. 2001). Sediment movement may appear as sediment waves through channel networks from headwater to downstream systems (Figure 1.7) (Benda and Dunne 1997b). Sediment deposits and accumulations induce local aggradation with the fining processes of sediment in the downstream direction. Such processes also modify channel reach types, sinuosity, and formation of side channels. Channels may shift laterally as banks erode and bars form in the unconfined floodplains of downstream reaches. Synchronized and desynchronized landslides and debris flows in headwater systems alter the impacts of sediment movement on geomorphic and biological conditions in downstream reaches (Figure 1.7). Synchronized landslides and debris flow deposits aggregate extensively within confined reaches of downstream channels during relatively short periods. In contrast, desynchronized mass movements gradually aggregate in larger reaches of channels. Sediment transit time from headwaters to the main channel depends on the presence of unconstrained reaches, tributary junction angles, channel gradient, timing of various mass movements, and amount of runoff (Benda and Cundy 1990; Bravard and Gilvear 1996; Nakamura et al. 2000).

However, sediment transport to downstream reaches is not as simple as shown in Figure 1.6. Woody debris often forms jam structures in the transition zone between headwaters and downstream reaches due to deposits from landslides and debris flows, fluvial transport, and recruitment from riparian areas (e.g., by windthrow and natural mortality). Log jams often store sediment for 40 to 50 years until the structures collapse or channel courses change (Hogan et al. 1995). Changing valley configurations, channel gradient, and material types also modify sediment transport from headwater to downstream systems (Whiting and Bradley 1993; Nakamura et al. 2000). Spatial distribution of mass movement occurrence influences sporadic sediment transport throughout network systems (Benda and Dunne 1997b).

1.3.2. Biological processes

Biological processes in headwater systems

Because forested headwater streams are typically narrow with closed riparian canopies, biological processes in hillslopes and streams (terrestrial and aquatic) are closely linked (Figures 1.1). Retention and routing of organic materials from allochthonous inputs (i.e., riparian and lateral input of leaf litter and woody debris) are important factors affecting biological processes in headwater systems (Table 1.1). Allochthonous energy sources are larger than autochthonous energy sources (e.g., primary production in streams) (Bilby and Bisson 1992). Because of relatively smaller discharges and greater roughness elements (e.g., boulders and woody debris), coarse particulate organic matter (CPOM ≥ 1 mm) tends to be stored behind in-stream obstructions, retained for longer periods in headwater channels, and transformed to smaller particles (Kiffney et al. 2000): such organic matter accumulation thus are important sources of food and habitat for macroinvertebrates (Richardson 1992). The dominant functional group of macroinvertebrates in headwater channels is shredders; they break larger particles into smaller sizes (Table 1.1) (Cummins et al. 1989). Fungi and bacteria also help to break CPOM into fine particulate organic matter (0.5 μm ≤ FPOM < 1 mm) and dissolved organic carbon (DOC), which could benefit secondary consumers (Heard and Richardson 1995). Terrestrially derived invertebrates that are associated with riparian vegetation are important for aquatic biota in headwater streams (Wipfli 1997). Riparian canopy closure also modifies heat and solar radiation available to stream channels (Table 1.1). Groundwater and subsurface flows from hillslopes and zero-order basins contribute nutrients (e.g., DOC and nitrate) and influence water temperature (Table 1.1). Availability of nutrients and light as well as water temperature modifies algal growth: this in turn alters rates of nutrient leaching and litter decomposition. Hyporheic zones and their nutrient exchange in headwaters are relatively smaller than those in downstream reaches (Stanford and Ward 1993). Lateral habitat diversity in riparian zones may be small because of the confined valleys of headwater streams, while longitudinal variation of habitat may be larger due to changes in discharge, channel gradient, and sediment supply. Transitional streams emerging from zero-order basins are also important habitat and sources of organic matter (Meyer and Wallace 2001).

Species composition and life history of vertebrates are also unique in headwaters. In the Pacific Northwest, there are relatively limited numbers and restricted species of fishes (e.g., cutthroat trout [*Oncorhynchus clarki*] and bull trout [*Salvelinus confluentus*]) occur because of the topographic harshness (steep channel gradients and shallow water). Due to geographical isolation, population of such trout may have unique genetic characteristics in headwater systems. Adult coho salmon (*Oncorhynchus kisutch*) spawn and some juvenile coho reside in refugia within lower headwater reaches during high flows (Bryant 1984). Some amphibians (e.g., tailed frogs [*Ascaphus truei*]) are also found primarily in headwater channels and associated riparian zones.

<u>*Responses and recovery from disturbances in headwater systems*</u>

The dynamic nature of geomorphic and hydrologic processes affects the biotic community through disturbances. The frequency, intensity, and duration of disturbances are important factors altering responses and recovery time of riparian vegetation, channel morphology, and biological communities (Townsend, 1989; Gregory et al. 1991; Swanson et al. 1998). Mass movement is the major disturbance in headwater channels, while forest fire, floods, and droughts also occur with varying frequencies (Table 1.1). The movement of sediment and woody debris during landslides and debris flows drastically alters in-channel habitat (e.g., pool depth and interval) and macroinvertebrate communities (Lamberti et al. 1991) (Table 1.1). Because of limited refugia and larger moving particles in relatively confined headwater channels, macroinvertebrates and fish may be killed or washed away during peak flows, or find refuge locally and in downstream reaches (Sedell et al. 1990).

Recovery processes in riparian and stream ecosystems differ according to level of disturbance. For instance, exposed bedrock is found in scour and runout zones of landslides and debris flows, and sediment and woody debris accumulations are distributed in deposition zones: this physical template characterizes the resistance and resilience of biotic communities and recovery processes from the disturbances. Either narrow bands of even-aged vegetation (typically alder [*Alnus* spp.] in the Pacific Northwest) or mixed conifer and deciduous riparian corridors may establish along headwater channels depending on the level of disturbance (e.g., level of soil damage). Such differences in riparian vegetation modify long-term recovery processes of the biological communities in headwater ecosystems because of changes in the recruitment of leaf litter, woody debris, and sediment (Bilby and Bisson 1992; Gomi et al. 2001). Recovery of headwater biotic communities from disturbances may also depend on the continuity of headwater systems. Aerial migration from undisturbed downstream to upstream reaches is important for recovery. If undisturbed sub-reaches exist in otherwise disturbed upper reaches, invertebrates and organic matter that drift to disturbed reaches may induce quicker recovery of biotic communities (Lamberti et al. 1991).

Seasonal drought significantly affects the life cycles and community structure of invertebrates in headwater systems (Dieterich and Anderson 2000; Muchow and Richardson 2000) (Table 1.1). Temporary streams with greater than 4 to 5 months flow duration have similar faunal assemblages, whereas life cycles of macroinvertebrates are altered in intermittent streams with less than 3 months of flow. During the dry periods, aquatic insects move to hyporheic zones, remnant wetted pools, and permanently flowing channels (e.g., downstream reaches and other streams). Aquatic invertebrates also emerge to adult forms and other desiccation-resistant forms, largely based on diapause. During much drier years, first- and second-order channels may be entirely dry and exert greater effects on macroinvertebrates.

Downstream assemblages in network systems

Materials from headwater tributaries modify downstream biological assemblages and processes in channel networks (Table 1.1). Spatial and temporal variation of riparian and channel structures related to the occurrence of mass movement as well as flow characteristics in headwater tributaries creates different patterns of biological assemblages in channel network systems. Changes in channel morphology from confined headwater systems to braided and meandering channels in downstream systems may affect interaction between riparian and stream ecosystems as well as habitat types (Ward and Stanford 1995). Sediment transport from tributaries affects the distribution of substrate sizes and thus modifies macroinvertebrate communities (Rice et al. 2001). Supplies of nutrients and organic matter to larger streams depend largely on inflows from tributaries. Most of the CPOM recruited in headwater streams (70 – 90 %) is transported downstream (Webster et al. 1999; Kiffney et al. 2000; Wipfli and Gregovich 2002). FPOM concentrations typically increase along headwater channels due to biological and physical processing (breakdown). Therefore, the CPOM/FPOM ratio may rapidly decrease with increasing drainage area because CPOM declines due to lower inputs relative to channel size and FPOM increases due to breakdown processes (Webster et al. 1999) (Table 1.1; Figure 1.4). Types of vegetation (deciduous and coniferous) related to mass movement and timber harvesting histories in headwater systems may modify the amount and seasonal variation of CPOM and FPOM export to downstreams (Kiffney et al. 2000). For instance, leaves from deciduous trees and shrubs typically decompose 2 to 3 months after entering streams, while conifer needles take 200 days to 2 years to be processed by bacteria and macroinvertebrates (Gregory et al. 1991). Drifting organic materials and macroinvertebrates from fishless headwater tributaries support both growth rates and density of stream vertebrates in downstream systems (Wipfli and Gregovich 2002). Therefore, the food webs and community structures of network watershed systems may be modified through the drifting of materials (invertebrates and detritus) from headwater tributaries.

Because of the different characteristics and magnitudes of disturbances, their impacts on biological communities in headwaters and downstream reaches will differ. A single debris flow may destroy biotic communities and habitat in headwater systems because of its acute impact. In downstream systems, however, collective effects of sediment transport and flood pulses and surges from headwater systems affect riparian vegetation and the biotic community (Table 1.1) (Nakamura et al. 2000). Basin wide drought may increase the number of intermittent reaches and decrease linkages between headwaters and main channels. However, more refugia such as side channels and undisturbed tributaries are accessible in downstream reaches compared to confined headwaters (Reice et al. 1990). The effects of disturbances in headwater systems on the channel network strongly relate to material routing processes from headwaters to downstream.

1.4. Linkages of headwater and network systems

The nature and degree of linkages between headwater and downstream systems are important aspects of the roles of headwater streams and routing processes of organic and inorganic matter. Linkage strength varies spatially and temporally due to topographic aspects and occurrences of mass movement: such characteristics relate to long-term geomorphic (e.g., glaciation and tectonic) activities and lithology (Sidle et al. 1985). Debris fans and flood plains are geomorphic attributes that support the linkages from headwaters to main channels. Sediment movement may be modified by channel gradient, tributary junction angle, and reach constraints (Benda and Cundy 1990; Nakamura et al. 2000). Beaver ponds, wetlands, and intermittent channel reaches also alter the connectivity between headwater to downstream systems. Intermittent channel reaches also disrupt the connectivity between headwater to downstream systems. In addition to spatial variation of connectivity, temporal variation related to the occurrence of mass movement, windthrow, wild fire, and landuse change as well as their respective recovery processes affect the degree of connection between headwater to downstream systems. Biologically, connectivity is important for species migration, habitat, and refugia (Sedell et al. 1990) and for the flux of organic matter and nutrients (Cummins et al. 1983).

Tributary junctions between headwater continua and larger channels are very important as network nodes for regulating material flows in watersheds and have unique hydrologic, geomorphic, and biological attributes. Higher heterogeneity of water, sediment, and woody debris movement occur at tributary junctions. Abrupt changes in channel gradient and valley width may cause sediment deposition, including terraces and debris fans. Riparian structure at such tributary junctions is complex because riparian vegetation is frequently destroyed by floods, sediment deposition, and scour. Plant seeds transported by headwater streams may initiate riparian regeneration. Channel geometry at tributary junctions varies depending on sediment and flow regimes from headwater systems and their degree of synchronization. Scour pools and gravel bars typically form along tributary flow margins depending on junction angles (Bristow et al. 1993). Such sediment and woody debris deposits modify channel forms – e.g., braiding and side channels. Hydrologic and geomorphic variability at tributary confluences also influences habitat types (pool size and distribution as well as substrate type) and biological processes in the area of the junction. Habitat, and therefore species composition, may be very diverse at confluences because sediment and woody debris accumulations form pools, steps, and side channels (Rice et al. 2001). Drifting materials from headwater tributaries also mix at junctions. Hyporheic processes should be enhanced at junctions due to the accumulation and exchange of materials, but this has not been studied. Both nutrient and gas exchange in the hyporheic zone would be significant when sediment and woody debris accumulate and braided channels form at confluences.

1.5. Summary and conclusions

The importance of headwater systems as sources of sediments, water, nutrients, and organic matter to downstream reaches has been articulated and emphasized. Despite the significant roles of headwater systems within the channel network, the ecological values of headwater systems are underestimated and their processes have been extensively modified by land use (e.g., Meyer and Wallace 2001). Different characteristics of processes in headwaters and larger watershed systems need to be considered for establishing management guidelines. Hydrologic, geomorphic, and biological processes in and along hillslopes, zero-order basins, transitional channels, and first- and second-order channels characterize headwater systems in the following ways: (1) processes are tightly linked between hillslopes and channels and from terrestrial to aquatic environments; (2) the expansion of hydrologically active areas (e.g., riparian zones, zero-order basins, bogs) during periods of increasing wetness increases the probability of mass movements and alters flow paths between terrestrial and aquatic environments; (3) landslides and debris flows that dominate geomorphic processes alter distributions and accumulations of sediment and woody debris; (4) recovery of invertebrate communities after such disturbances depends on drift, migration, and recolonization of biota from undisturbed upper and lower reaches; and (5) succession and conversion from deciduous to coniferous riparian stands (and *vice versa*) modify availability of nutrients and light, recruitment of wood and organic materials, habitat types, and structure of biotic communities.

The numerous headwater tributaries that flow into downstream reaches affect hydrologic, geomorphic, and biological processes and attributes in downstream reaches of channel networks in the following ways: (1) synchronized or desynchronized inflows of water, sediments, nutrients, and organic matter from headwater tributaries create a variety of channel conditions and biological assemblages in downstreams reaches; (2) temporal variations of disturbance regimes and riparian succession in headwater tributaries alter physical and biological conditions of channels as well as input of materials (sediment, invertebrates, and detritus): this in turns modifies food webs and their productivity in downstream reaches ; (3) connectivity of headwater systems to downstream reaches affects both the cumulative and dispersed nature of material transport processes within watershed systems; (4) tributary junctions are unique in their physical and biological processes and are important as network nodes; and (5) spatial and temporal variations of processes in headwater systems are critical factors affecting the dynamics of stream ecosystems as well as heterogeneity of riparian and riverine landscapes in channel networks.

Because the characteristics of headwaters vary due to biogeoclimatic factors (e.g., riparian structure, precipitation, discharge, drainage density) and management and disturbance regimes, both similarities and differences of processes among headwater systems are important for evaluating the role of headwaters within the watershed network. Two general types of studies are needed to understand headwater processes and downstream linkages. Process-related studies within headwater systems are essential. Despite the progress in elucidating hydrogeomorphic (e.g., Sidle et al. 2000) and biological (e.g., Richardson 1992; Wallace et al. 1999) processes from hillslopes to stream channels, a better understanding of the functional linkages among wood, sediment, nutrients, and water in headwater systems is needed to address the relevant ecosystem process. It is also necessary to evaluate the influence of headwater processes on downstream systems (e.g., Benda and Dunne 1997b; Rice et al. 2001; Wipfli and Gregovich 2002). The connectivity of headwaters to downstream reaches must be evaluated in future studies to understand cumulative effects of changes in headwaters.

Ecology and management of downstream riparian zones have been extensively studied and applied in the context of stream restoration during the past 10 years (Naiman et al. 2000). However, recently the role of headwater systems has attracted more attention with respect to conservation, restoration, and management of downstream reaches. Consequently, management of headwater streams and riparian zones is important and there are benefits to considering the linkages of headwater and downstream systems. The collection of appropriate information will require collaboration of interdisciplinary teams of hydrologists, geomorphologists, and biologists.

Table 1.1 Characteristics of hydrologic, geomorphic, and biological processes in headwater and network systems.

		Headwater system	Network system
Hydrology	*Precipitation*	• Greater precipitation • Greater snow accumulation	• Lower snow accumulation
	Heat dynamics	• Canopy closure • Depending on groundwater flow	• Canopy open
	Flow generation	• Subsurface and groundwater flow in zero-order basins and hillslopes	• Subsurface flows in flood plain riparian • Tributary outflows
	Flow regime	• *Smaller absolute discharge volume* • *Greater variation of unit-area peak discharge*	• *Larger absolute discharge volume* • *Smaller variation of unit-area peak discharge* • *Synchronized or desynchronized outflows*
	Hyporheic zone	• Smaller volume	• Greater lateral and vertical volume
	Stream chemistry	• Soil pores, bedrock fractures, lithology • Flow path in hillslopes and zero-order basin	• Tributaries outflow, Hyporheic exchange
Geomorphology	*Morphology*	• Higher mean altitude • Steeper gradient and confined valley	• Lower mean altitude • Lower gradient and wider valley
	Dominant sediment movement	• Episodic mass movement	• Chronic bedload movement
	Channel reach type	• Colluvial, Cascade, Step-pool, Bedrock	• Step-pool, Pool-riffle, Ripple-dune
	Roughness element	• Woody debris, boulder, bed form (e.g., step)	• Woody debris, logjams, bed form (e.g., bar)
Biology	*Energy input*	• Allochthonous and lateral (from hillslope) input	• Autochthonous and tributary outflows
	Organic matter	• CPOM > FPOM • DOC from groundwater flows and leaching	• CPOM < FPOM • DOC from tributaries and in-stream processing
	Nutrient sources	• Groundwater, riparian vegetation	• Tributary outflows, floodplain
	Dominant functional group	• Shredder	• Gatherer, Filterer
	Disturbance	• Landslides and debris flows • Drought	• Flood plus and bedload movement

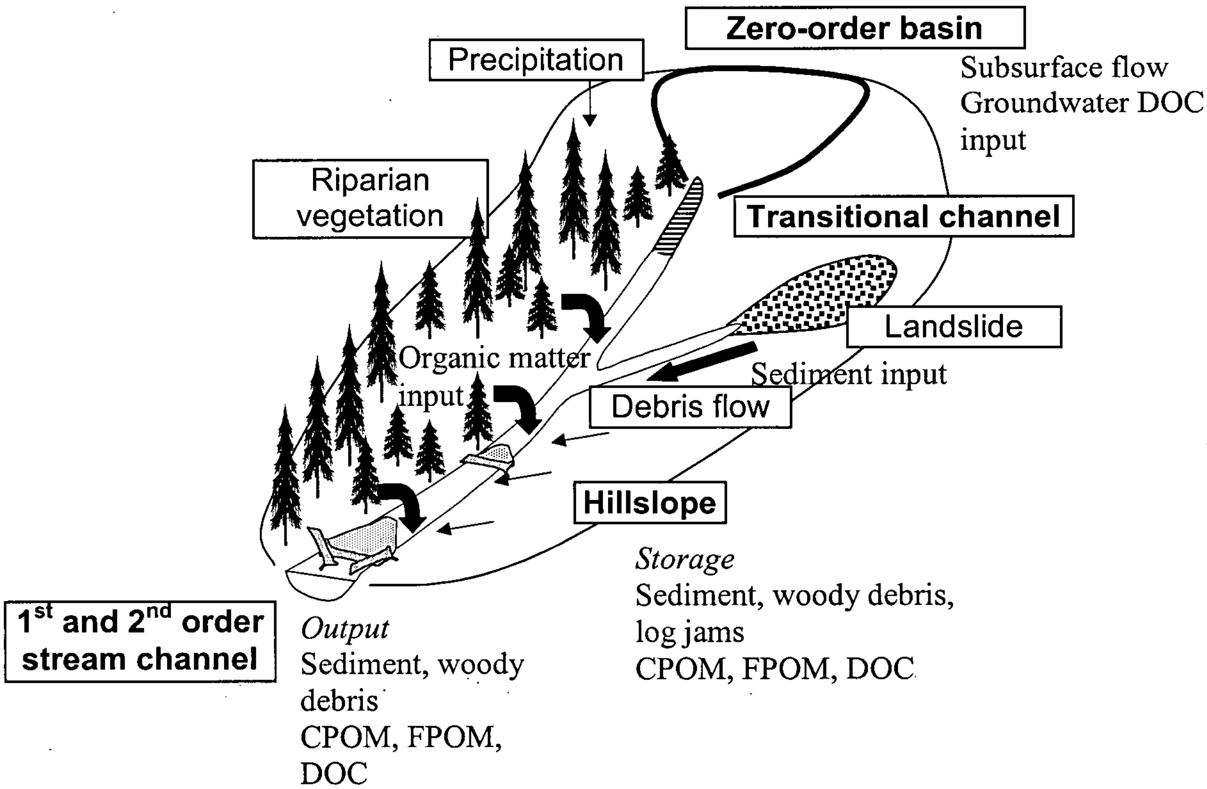


Figure 1.1 Processes and structures in headwater continua. Four topographic units (bold type), including hillslopes, zero-order basins, intermittent channels emerging from zero-order basins (transitional channels), and 1st and 2nd order stream channels, compose headwater systems.

Figure 1.2 an example of a forested headwater stream. This photo was taken looking upstream.

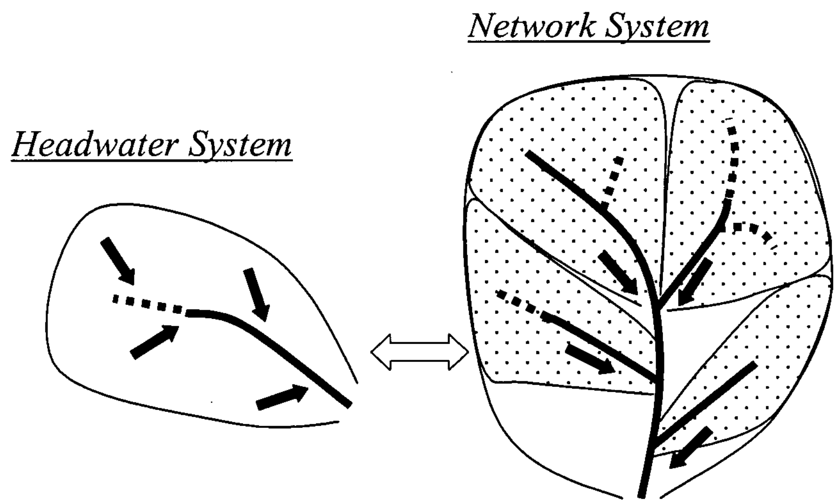


Figure 1.3 Structural differences between headwater and network systems with arrows showing the movement of sediment, water, nutrients, and organic material. Solid and broken lines show perennial and intermittent stream, respectively.

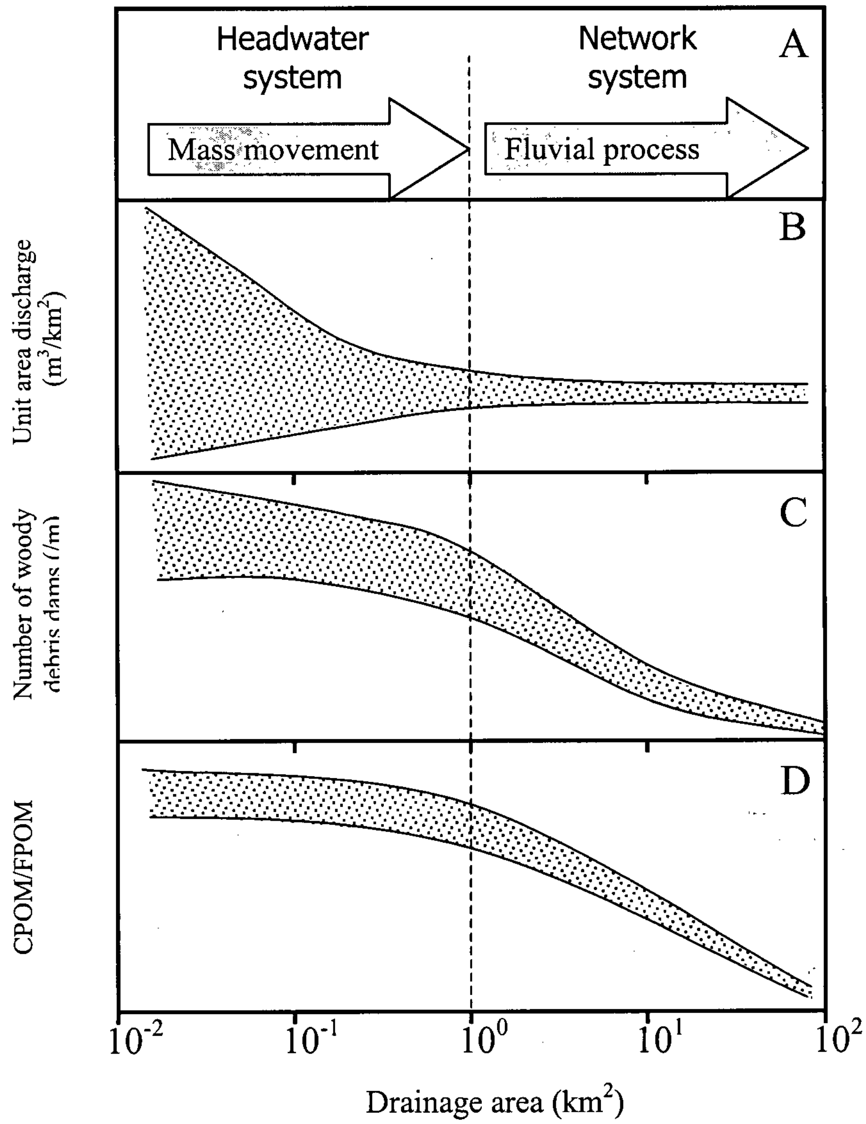


Figure 1.4 Downstream changes of hydrologic, geomorphic, and biological processes. Shaded area indicates ranges of each parameter. Transition from debris flow-dominated to alluvial-dominated processes occur at drainages area ranging from 0.1 to 1.0 km^2 (Figure 3A) (Benda and Dunne 1987). Variation of unit area discharge is greater within basins < 1.0 km^2 (Figure 3B) (Woods et al. 1995). Numbers of woody debris dams in headwater streams without mass movement is greater compared to larger watershed systems because relatively smaller woody debris forms woody debris dams (Figure 3C). CPOM/FPOM ratio may rapidly decease in drainages > 1.0 km^2 because CPOM is retained more in headwater streams and greater amounts of FPOM are transported from headwaters (Figure 3D).

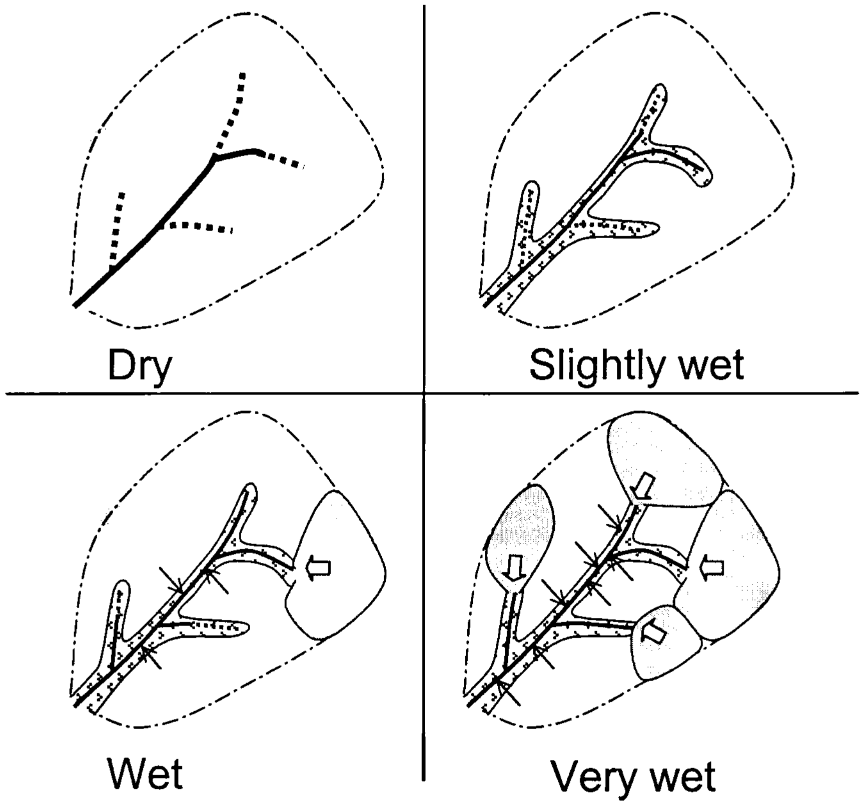


Figure 1.5 Conceptual view of dynamic, hydrologically active areas in headwaters (modified from Sidle et al. 2000). For dry conditions, riparian zones and direct precipitation on channels are the only active sites of flow generation. Throughflow from the soil matrix in the foot of hillslopes and riparian areas gradually activates with increasing wetness. Zero-order basins (shaded areas) with relatively shallow soils begin to contribute surface runoff (large arrows) during wet conditions, while preferential flow (small arrows) from hillslopes contributes less to stream flow. Flow begins to occur in transitional channels emerging from zero-order basins. Zero-order basins and preferential flow actively contribute to storm flow during very wet conditions.

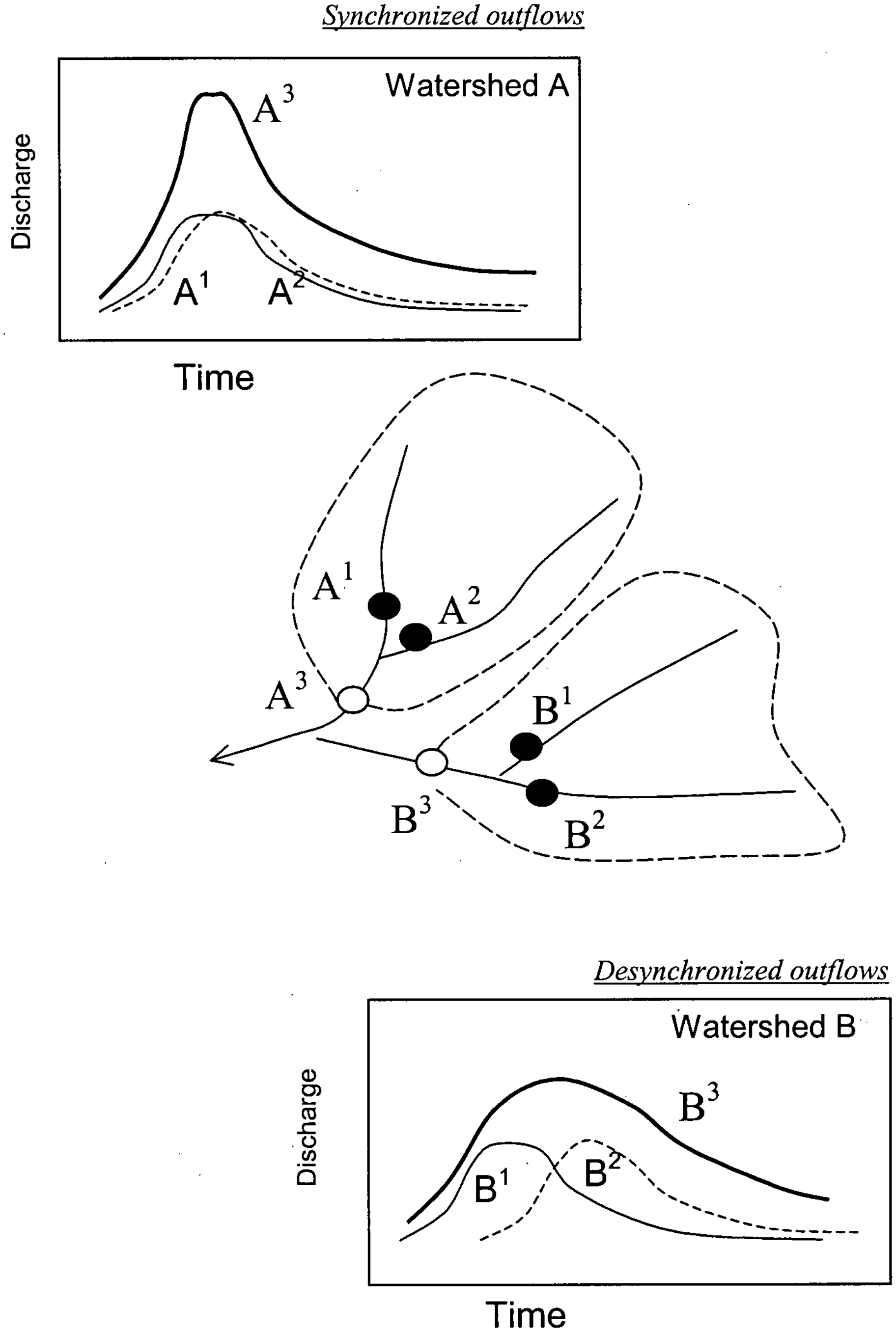


Figure 1.6 Synchronization of hydrologic processes in network systems (modified from Ziemer and Lisle 1998). Volumes of outflows in tributaries of watershed A and B are similar; however, peak discharges are different at A^3 and B^3 because of the different arrival time of peak flow.

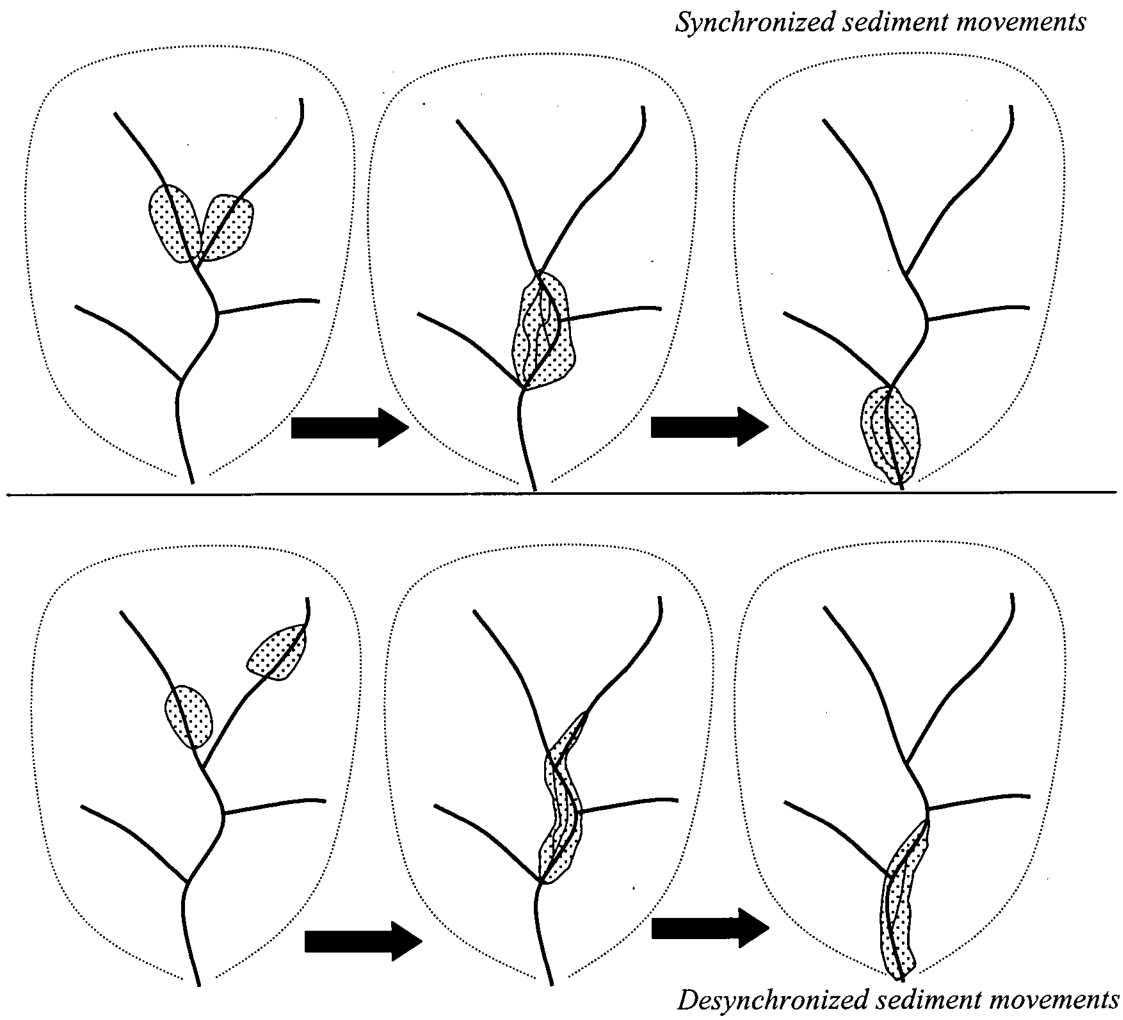


Figure 1.7 Synchronization of sediment movement in branched watershed systems (modified from Montgomery and Buffington 1998). Shaded area shows sedimentation due to landslides and debris flows. Accumulated sediments from headwater systems may alter the formation of braided and side channels.

Chapter 2

Characteristics of sediment and woody debris distribution and the function of woody debris for storing sediment

2.1. Introduction

A number of studies during last three decades have demonstrated the biological and geomorphological importance of woody debris in forested streams (e.g., Harmon et al. 1986; Bisson et al. 1987). Woody debris can alter flow velocity and direction and thus exert control over sediment and organic matter transport as well as stream geomorphology (Woodsmith and Swanson 1997). Therefore, woody debris modifies the structure and abundance of habitat as well as provides a source of nutrients for stream biota (Bilby and Ward 1989; Inoue and Nakano 1998). Woody debris also forms steps and modifies the hydraulics of mountain stream channels (Heede 1972). Changes in the abundance of woody debris in streams control sediment movement (Megahan 1982; Nakamura and Swanson 1993; Bovis et al. 1998), pool spacing (Montgomery et al. 1995), and streambed composition (Sidle and Sharma, 1996; Woodsmith and Buffington 1996).

Timber harvesting and related landslides and debris flows strongly affect stream geometry and the persistence of woody debris (Bisson et al. 1987). Higher volumes of woody debris were found in unlogged streams compared to logged streams in the Appalachian Mountains (Hedman et al. 1996). Similarly, recent research in the Pacific Northwest observed reduced numbers of woody debris pieces in streams after logging (Bilby and Ward 1991). In contrast, earlier research in the Pacific Northwest showed that the numbers of woody debris pieces increased after logging due to logging slash and unmerchandible timber (Froehlich 1973; Bryant 1980). Hogan et al. (1998) indicated that formation of log jams were related to the history of landslides after logging in the Queen Charlotte Islands, British Columbia.

Both timber harvesting and related soil mass movement can significantly impact headwater streams. Headwater streams are defined as small (bankfull width < 2 m), steep gradient (> 3°) channels that include first- and second-order streams (Strahler 1957) and zero-order basins (Tsukamoto et al. 1982). While hillslope gullies have relatively deep (3-30 m) V-shaped cross-sections (Bovis et al. 1998), headwater streams may have either shallow (1-3 m), U-shaped profiles or gully-like profiles. Headwater streams are abundant in mountainous terrain of the Pacific Northwest.

The distribution and accumulation of woody debris in headwater streams may be more directly affected by timber harvesting and related sediment movement than in larger, low gradient streams. For instance, logging slash and unmerchandable logs remain in the streams after timber harvesting (Froehlich 1973; Millard 2000). Logging roads, which cross headwater streams, often alter stream channels due to culvert installations, modify flow and sediment regimes, and increase landslide probability (Sidle et al. 1985). Wood and sediment are evacuated from upper stream reaches by landslides/debris flows and then redistributed and deposited in downstream reaches (Johnson et al. 2000). Subsequently, pioneer vegetation species rapidly recolonize in both scour and deposition zones and new woody debris is introduced gradually into headwater channels (Swanson et al. 1998). This newly recruited woody debris provides sites for sediment storage. These processes modify the biological productivity, microinvertebrate habitat, and sediment linkages from hillslopes to streams and from headwaters to main channels.

Even though various attributes of headwater streams related to biological and physical stream dynamics are recognized, the relative importance of these small channels compared with higher order and fish bearing streams is often underestimated. Particularly, functional linkages between headwater streams and main channels are poorly understood. A tight biological coupling exists between organic matter inputs and macroinvertebrate habitat in headwater streams (Richardson 1992). Drifting materials (invertebrates and detritus) from headwater streams are important components for food webs in the downstream ecosystems (Wipfli and Gregovich 2001). Portions of headwater streams in lower gradient sections are also important for migration, refugia, and habitat of juvenile fish (Bryant 1984). Sediment movement and floods in headwater systems affect the channel geomorphology and riparian vegetation structure in headwaters and downstream reaches (Swanson et al. 1998). Sediment transport from steep headwaters to downstream is closely related to the sediment storage capacity of woody debris (Megahan 1982; Bovis et al. 1998). Although the river continuum concept (Vannote et al. 1980), which incorporates physical and biological stream attributes, is widely accepted; headwater streams have typically not been included in this conceptual model, supported studies, and management applications. Thus, the influence of timber harvesting on woody debris and sediment dynamics in headwater streams is poorly understood.

The objective of this study is to estimate the influence of different riparian conditions related to timber harvesting and landslide activities (management/disturbance regimes) on woody debris and sediment distributions and their related functions in headwater stream systems. We examined: (1) the influences of recent and past timber harvesting on the abundance and distribution of woody debris; (2) the influences of landslides/debris flows on woody debris abundance and sediment accumulations; and (3) the in-stream functions of woody debris related to sediment storage.

2.2. Study site

This study was conducted in the Maybeso Experimental Forest and the adjacent Harris River basin in the Tongass National Forest, Prince of Wales Island, southeast Alaska (Figure 2.1). Climate in this area is cool and temperate. The mean annual temperature is 10°C; mean annual precipitation is 2800 mm. The basins are U-shaped glacial valleys. The valleys are covered by a varying thickness of glacial till that was formed during late Wisconsinan glacial advance (Swanston 1967). Depth of soil plus the thin veneer of glacial till ranges from 0.30 to 1.0 m. Forest vegetation is dominated by western hemlock (*Tsuga heterophylla*), Sitka spruce (*Pieces sitchensis*), western red cedar (*Thuja plicata*) and red alder (*Alunus rubra*); however, riparian vegetation is highly influenced by past disturbance regimes. Alder dominates riparian zones that have been disturbed by landslides and debris flows. No residential fish were found in the upper reaches of the headwater streams, although a few juvenile salmonids were found in the lower. The Maybeso Valley was initially logged in 1953 and logging continued until 1957. Timber harvesting was conducted from 1959 to 1961 in the Harris River basin (Meehan et al. 1969). More recent clear-cutting occurred in the Harris River basin in 1995 with relatively smaller cut-blocks. All harvest units were clear-cut using cable-logging methods on hillslopes.

Five management/disturbance regimes (treatments) in riparian zones of headwater streams were selected based on the history of timber harvesting and landslides/debris flows within the Maybeso Experimental Forest and the Harris River basin (Figure 2.1). The five treatments include: old-growth (OG); recent (3 year old) clear-cut (CC); young-growth (37 year after clear-cutting) conifer riparian forest (YC); young-growth (40 year after clear-cutting) alder riparian forest (YA); and recent landslide/debris flow channels (LS) (Table 2.1, Figure 2.2 and 2.3). Three headwater streams were examined for each of the five treatments giving a total of 15 streams. These treatments are representative of steep glaciated forest landscapes in southeast Alaska since they are largely controlled by similar biogeoclimatic factors typical of the area (e.g. vegetation, glaciation, and geology). LS and YA streams were affected by timber harvesting and once or twice by landslides/debris flows in 1961, 1979, and 1993 based field studies (Swanston 1967; Johnson et al. 2000), aerial photographs taken by USDA Forest Service, and tree ring analysis of trees growing on debris flow deposits. The most recent landslide activity occurred during an October 1993 rainstorm and affected only LS channels (Figure 2.2). Once landslides initiate, sediment is transported as channelized debris flows and deposits in lower gradient reaches. Debris flows also transport woody debris and newly recruited wood as well as form woody debris jams in the deposition zones. The lower ends of the deposition zones did not reach the main channel of Maybeso Creek due to the wide, flat valley bottom (Figure 2.4).

To evaluate the influence of landslides/debris flows on the distribution and accumulation of woody debris, both LS and YA streams were divided into upper (scour and runout) and lower (deposition) sections based on field observations (Figure 2.4). Additionally, two CC streams (CC1 and 2) were divided into upper and lower sections to estimate the effects of a mid-slope logging road on woody debris and sediment distribution. The effects of landslides/debris flows and subsequent regeneration of riparian stands were evaluated by comparing the LS, YA, and OG streams.

Comparing YC, CC, and OG streams demonstrate the influence of past and recent timber harvesting in channels with no landslide/debris flow activity during the past few centuries.

The lengths of upper channel reaches range from 100 to 340 m with mean bankfull widths of 0.6 to 2.8 m and mean stream gradients of 8.5 to 45.9 % (Table 2.1). The lengths of lower channel reaches in LS, YA, and CC range from 100 to 400 m with mean bankfull widths of 0.9 to 3.7 m and mean stream gradients of 9.4 to 32.5 %. Elevations from lower to upper ends of study reaches range from 80 to 270 m in YA and LS, while those in YC, CC, and OG range from 150 to 330 m. Stream channel profiles are only incised 1 to 3 m. Most of the streams are perennial but several appear to be ephemeral during seasonally dry periods. Because soil is shallow in the study area (Swanston 1967), bedrock was naturally exposed in 13.4 and 26.9 % of the channel sections in OG1 and OG2 channels, respectively. Moreover, due to extensive landslide/debris flow scour and runout, the upper sections of LS and YA channels had 25 to 60 % exposed bedrock (Table 2.1).

2.3. Methodology

Field methods

Representative channel reaches were intensively investigated during the period from June to August 1998. Stream gradient and cross-sectional profiles were surveyed using an engineer's level, stadia rod, and tapes. Stream elevation was measured at 5 m intervals and at each significant slope break. For example, the upper and lower boundaries of log steps and the front and back of sediment wedges were surveyed. Exposed bedrock length and its position in the channels were also measured. The wetted and bankfull widths of streams were estimated every 5 m. Bankfull width was defined by the presence of moss and rooted vegetation along the channel margins and the top of banks. Three cross sections in each stream were surveyed to describe valley and channel profiles. At the three cross sections, the median diameters of 100 pebbles in a 0.2×0.2 m grid were measured to provide an indication of mobile streambed material (Wolman 1954). Large cobble and bolder components > 0.2

m were excluded because of their relative immobility except during landslide/debris flow events. Watershed area for each stream was calculated from topographic maps (US Geological Survey, Craig C-3 and B-3; 1991) using a digital planimeter.

Organic debris in streams was divided into woody debris and fine organic debris (FOD). Woody debris was further classified into two categories: (1) large woody debris (LWD) - pieces ≥ 0.5 m in length and ≥ 0.1 m in diameter and (2) fine woody debris (FWD) - pieces ≥ 0.5 m in length and 0.03 to 0.1 m in diameter. To quantify the distribution and accumulation of woody debris at each site, the following properties of LWD were measured: in-channel, bankfull, and total lengths; diameter; position; and orientation. In-channel length was measured for either a portion or the entire length of LWD pieces located within the wetted channel width that significantly dissipated flow energy and affected sediment transport. Bankfull length was defined as either a portion or the entire length of LWD pieces within bankfull width. Total length was measured for entire pieces of LWD including terrestrial portions. Diameter at the middle of each woody debris piece was recorded. Volume (m^3) of LWD (V) was calculated as follows for the in-channel, bankfull, and total volume components of LWD:

$$V = \pi \times (D/2)^2 \times L \qquad [1]$$

where D and L are the mid-log diameters and appropriate lengths, respectively (Robison and Beschta 1990). Even though several studies applied a volume equation using end diameters of LWD pieces (Nakamura and Swanson 1993; Inoue and Nakano 1998), we used only median diameter as an approximation for estimating LWD volumes because of our small stream widths. All LWD pieces were classified as functional (interacting directly with streams), transitional (not directly interacting with streams, but suspended just above streams and decomposed enough to interact with streams in the near future), and non-functional (no interaction with streams and/or suspended well above channels). Orientation of LWD was measured in relation to a line parallel to the channel axis to determine the degree of interaction of LWD pieces with streams. Both left (+) and right (-) hand orientations of LWD from 0° to 90° were recorded in ±5° intervals. LWD recruitment in CC sites was divided into three types based on the period of recruitment: (1) recent recruitment (i.e., just after logging); (2) during logging; and (3) before logging. These groupings were based on field inspection of cutting edges and decay in woody debris. FWD was surveyed for channel position and number of pieces. Volumes of fine organic debris (FOD), such as accumulations of leaves, branches, and fine logging slash were categorized as small ($< 0.01\ m^3$), medium (0.01 to $0.1\ m^3$), and large ($\geq 0.1\ m^3$) volumes where FOD accumulations contributed to and/or formed a sediment wedge.

Sediment storage behind woody debris and other obstructions (e.g., rock and bedrock) was measured in these headwater streams based on the geometry of sediment wedge [width (w), length of the wedge (L_w), and average depth at the front of the wedge (d)]. Average depth of the sediment wedge was measured using a sediment probe at several points. The cause of sediment deposition was categorized according to the formation elements of debris dam: LWD, FWD, FOD, rocks, and bedrock. The volume of sediment stored behind woody debris and other obstructions was computed based on rectilinear pyramid,

$$\text{Sediment volume} = (w \times L_w \times d)/3 \qquad [2]$$

The approximation of a pyramid shaped wedge appears appropriate since the upstream end of stored sediment typically converges to a point in these small channels. Sediment storage ratio, determined as the volume of sediment behind woody debris divided by volume of all stored sediment, was assessed to estimate the relative contribution of woody debris for storing sediment.

Statistical methods

Three levels of hierarchical structure in statistical analysis were: treatments; sites within treatments; and 20-m consecutive reaches within sites. Treatments (LS, YA, YC, CC, and OG) were fixed factors, while sites (1, 2, and 3) nested within each treatment were considered random factors. Thus, a mixed effect procedure was conducted to assess treatment effects (Neter et al. 1996). For these analyses, the lower (depositional) reaches of LS, YA, and CC channels we excluded. All 15 sites were divided into consecutive 20-m reaches to test the treatment effects on distribution and abundance of woody debris and sediment. At the scale of these 20 m reaches (about an order of magnitude greater than bankfull width), woody debris, sediment and channel morphology are governed by relatively uniform hydrologic and geomorphic processes (Frissell et al. 1986). Because consecutive 20-m reaches might be correlated with each other, repeated measurement effects were also incorporated in the statistical model.

The PROC MIXED procedure of SAS version 8 was used for analyzing the mixed effects model (Littell et al. 1999). This procedure permits the inclusion of an unequal number of samples (i.e., 20-m reaches) in the analysis. Number and volume of LWD (in-channel and total), number of FWD pieces, total volume of sediment, and volume of sediment stored behind woody debris were measured in each 20 m section. Channel gradient and bankfull width were related to the abundance, distribution, and in-stream function of woody debris (e.g., Bilby and Ward 1989). Thus, stream gradient and average bankfull width in the 20 m reaches were used as covariate terms in the statistical models. If interaction terms such as treatment × stream gradient and treatment × bankfull width were significant in the mixed-effect analysis of covariance (ANCOVA), relationships among the dependent variables and stream gradient and bankfull width were assessed. If interaction terms were not significant, the mixed-effect analysis of covariance (ANCOVA), including treatment and two covariate effects (channel gradient and bankfull width), was conducted to assess treatment effects (Neter et al. 1996). In this case, the reduced model (i.e., without interaction terms) was compared to the full model based on AIC (Akaike Information Criterion) (Littell et al. 1999). Then, if treatment effects were significant, Bonferroni multiple comparisons were conducted to estimate the differences among treatments. The upper and lower sections in LS, YA, and CC sites were compared in a separate analysis. Lengths and diameters of LWD pieces in each treatment were statistically compared using the Wilcoxson Rank sum test because the sizes of LWD pieces were strongly skewed. A significance level of $\alpha = 0.05$ was used for all statistical analyses.

The mixed effect ANCOVA model using PROC MIXED procedure was also applied to analyze total sediment volume, volume of sediment stored behind woody debris, and sediment storage ratio in each 20 m reach. The numbers of LWD and FWD pieces, volume of LWD, estimated volume of FOD, stream gradient, and bankfull width were used as covariate terms in the full models.

It was also hypothesized that the different types of woody debris (LWD, FWD, and FOD) had different functions related to sediment storage among treatments. Thus, the sediment storage behind woody debris in each treatment was evaluated using a linear regression model to indicate the influence of stream conditions and woody debris characteristics. Significant independent variables in the full model (number of LWD and FWD pieces, volume of LWD, accumulation of FOD, stream gradient, and bankfull width) were selected by a stepwise procedure with Cp statistics (Neter et al. 1996). Null hypotheses that the coefficients of independent variables in the regression models are zero were tested at $\alpha = 0.05$ level. All variables in this study were log (x+1) transformed to meet the assumption of normality and variance equality.

It was not possible to randomly sample streams in the study landscape because treatments were dictated by external geomorphic factors (i.e., YA and LS), management effects (i.e., YC and CC) and natural conditions (i.e., OG). Thus, a fixed model of treatment effects was employed in this observational study. Additionally, there were limited numbers of certain stream types in the area. Also, the size and largely perennial nature of the required headwater systems as well as the need ensure a continuity of processes within each system limited our choices of steams in the landscape. Therefore, it was difficult to truly randomize sites within each treatment. Nevertheless, we rely on the robustness of statistical procedures to draw inferences related to treatments. We assume that the five stream types (treatments) cover the entire population of streams in the area. To further support our approach and inferences, we note that the landscape from which the streams were selected has basically the same lithology, soils, climate, hydrological processes, natural vegetation, and geomorphic processes (i.e., glaciation and deposition of till). In such humid terrain, aspect has little influence on hydrological processes. Thus, aside from the obvious "external' management and geomorphic perturbations that dictated our treatments, the 'original' landscape and climate was uniform; this should minimize any confounding effect of the landscape (i.e., selection bias).

2.4. Results and discussion

2.4.1. Characteristics of LWD pieces

The distributions of diameter and length of LWD pieces were highly skewed to the smallest size classes in all streams (Figure 2.5). Thus, median diameters and median lengths were used to represent central tendencies for each treatment. Median diameters of total LWD ranged from 0.15 to 0.24 m (Table 2.2). Relatively larger diameters were found in YC (0.24 m) and OG (0.20 m) streams. Although other research in undisturbed streams of southeast Alaska found that 10 to 25 % of LWD pieces were > 0.6 m (Murphy and Koski 1989), we found that only 7.1 and 6.8 % of LWD pieces were > 0.6 m in OG and YC headwater channels, respectively. In LS, YA, and CC channels, only 1.4 to 2.7 % of LWD pieces were > 0.6 m. According to the Wilcoxson rank sum test, diameters of LWD pieces in LS, YA, and CC were significantly smaller than those in the OG and YC channels.

Median lengths of entire LWD pieces ranged from 1.5 to 2.5 m in each treatment. There were few pieces of LWD ≥ 10m in LS (3.4 %), YC (2.7 %), and CC (0.4 %) streams compared to OG (6.6 %). Due to the regeneration and subsequent mortality of young alder stands, many alder logs were suspended above streams and interacted with streams without breakage. Thus, relatively large numbers of long LWD pieces (≥ 10 m) were found in YA (7.5 %). Lengths of LWD pieces in LS and CC were significantly shorter than in OG ($p < 0.001$ and $p = 0.002$). Lengths of LWD pieces in YA were slightly longer than in OG ($p = 0.002$).

LWD volumes per piece in all study streams ranged from 0.1 to 1.1 m^3 and was small compared to other studies in the region that focused on lower gradient, wider streams in old-growth forests (Murphy and Koski 1989; Robison and Beschta 1990). Swanson et al. (1984) noted that the size of LWD was smaller in southeast Alaska than in Oregon and Washington. Since large diameter and valuable old-growth forests in southeast Alaska have been logged during past 50 years, the remaining old growth tends to have smaller diameters and lower productivity. Despite this limitation for selecting old-growth streams, our OG sites represent existing old-growth headwater channels in southeast Alaska in which the recruitment and function of woody debris play important roles.

Both diameters and lengths of LWD pieces were significantly smaller in upper sections of LS compared to lower reaches. In contrast, lengths of LWD in lower YA channels were significantly shorter than in upper YA. The differences of LWD size with respect to upper and lower reaches of LS and YA might be related to the regeneration of young alder stands after landslides and debris flows and their subsequent mortality. There were no significant differences in LWD diameters between the lower and upper reaches of YA and CC. Lengths of LWD pieces in upper and lower CC sections were not significantly different.

The percentage of all LWD pieces that directly interacted with the 15 streams averaged 68.5 % and ranged from 53.5 to 89.1 %. Sites without recognizable landslides and debris flows had a relatively constant percentage of LWD that directly interacted with channels; landslide channels had a higher variability of interactive LWD. Due to landslide deposition, a higher percentage (53 to 89 %) of interactive LWD was observed in the lower sections of LS and YA. About 50 to 70 % of LWD was oriented from 0° to ±45° with respect to the channel; however, no significant differences in orientation were found among various treatments.

2.4.2. Effects of timber harvesting on the abundance of LWD

For all analyses related to treatment effects, the interactions between treatment × stream gradient and treatment × bankfull width were not significant, thus treatment effects were assessed by the mixed effect ANCOVA model (Table 2.3). Additionally, based on AIC, the reduced model (i.e., without interaction terms) had a better fit than the full model (Littell et al. 1996). The in-channel numbers of LWD pieces were significantly higher in YC and CC compared to numbers in OG, YA, and LS streams (Table 2.3). The total numbers of LWD in OG streams were significantly smaller that in CC, but were not significantly different compared to YC. The abundance of LWD in both CC and YC channels increased because of the recruitment of LWD during past and recent logging activities. The number of LWD pieces was highest in the YC streams even though logging activities concluded three decades ago and woody debris has been gradually decomposing.

No significant differences in total and in-channel volumes of LWD were found among OG, CC, and YC streams (Table 2.3). However, total volume of LWD per 100 m in YC was twice that in OG. Total volume of LWD per 100m associated with CC channels was half that in OG channels; however, the majority of this volume in OG systems was outside the bankfull area. The higher numbers and volumes of LWD in YC streams (mean total LWD pieces 82.7 and in-channel 45.0 pieces/100 m) are attributed to large inputs from logging in the early 1960's. In some sections of YC, the stream flowed under "tunnels" of LWD even though much rotten wood was evident. Tree falling and yarding techniques affect debris recruitment into headwater streams and LWD levels can vary in managed forested streams (Froehlich 1973). Thus, past and recent logging activities appear to affect the distribution and abundance of LWD in headwater streams. The logging road through the CC channels did not significantly alter the abundance and distribution of woody debris below the road.

Although the numbers of LWD pieces in both CC and YC streams increased due to logging, the sizes and volumes of LWD in CC and YC differ (Figure 2.6 and Table 2.2). During the past 50 years, the amount and size of logging residue in harvested areas has changed with changing timber utilization, stand conditions, and logging and transportation techniques (Harris and Farr 1974). The standard for timber utilization has improved because of a variety of market conditions and upgrades in timber technology and industry. Before pulpmills were established in southeast Alaska in 1953, only high quality Sitka spruce and western hemlock were merchantable. In contrast, much low quality timber has value in the present market. Although western red cedar and yellow cedar have the highest value today, cedars were unused during 1950's. When loggers encountered cedars, they were normally cut and left in the woods (Harris and Farr 1974). Such practices led to abundant accumulations of large cedar in YC channels. In addition, logging and timber transportation systems are usually designed for the largest class of logs. Thus, such systems may not be suitable for handling smaller logs and broken pieces. With such technical limitations, even-aged stands are more preferable for cutting and less logging residue is generated compared to harvesting mixed aged stands (Harris and Farr 1974). By evaluating stump diameters, it is evident that trees harvested near YC channels in the 1950's and early 1960's were much larger and of greater age diversity than trees cut in 1995 at CC sites.

While we observed increases in the numbers of pieces of LWD (in-channel and total) in YC and CC due to timber harvesting, Murphy et al. (1986) found 54 % less LWD pieces in clear-cut streams compared to old-growth channels in larger, low-gradient streams of southeast Alaska. Lower numbers of LWD pieces were also found in logged streams in southwestern Washington (Bilby and Ward 1991). Ralph et al. (1994) found no significant differences in the number of LWD pieces among unharvested, moderately harvested, and intensively harvested streams in western Washington. In contrast, Froehlich (1973) reported that logging resulted in a 2- to 10-fold higher recruitment of woody debris (i.e., slash) compared to natural debris in steep headwater streams of Oregon.

The conflicting findings from these studies and our research can be attributed to: (1) changing management guidelines related to logging activities, including buffer strip leave areas; and (2) modification of recruitment and distribution of woody debris after and during logging, including the time lag of recruitment. Management regulations for woody debris and riparian buffers have changed dramatically because of concerns related to fish and wildlife habitat. Because of forest practices codes and rules that have been established and upgraded in the Pacific Northwest during the past few decades, damage to fish bearing streams has been reduced and very large accumulations of logging-related woody debris have been partly removed in larger streams (Bisson et al. 1987). Thus, under current forest practices, such accumulations in fish bearing streams are less frequent compared with earlier logging operations. Riparian buffer strips are designed to minimize impacts of timber harvesting on water temperature, bank erosion, and woody debris loading. Without buffer strips, LWD recruitment from riparian stands would be drastically reduced after logging. If continual inputs of woody debris to streams are not sustained, existing debris will wash away and decay, thus reducing the numbers of pieces. In contrast, logging residues and blow down from riparian stands can increase the numbers of LWD pieces after logging (Froehlich 1973; Bryant 1980). Despite such considerations in lower gradient streams, steep and small headwater streams have not been carefully managed for long-term recruitment and function of woody debris. From 36 to 60 % of LWD in our CC channels was recruited during and just after logging. Volume of LWD recruited during logging and just after logging activities ranged from 2.6 to 7.0 m^3/100 m in the three CC channels. Although the amount of LWD added by logging activities was relatively small compared to levels reported by Froehlich (1973), these inputs are significant in small headwater streams. Moreover, evidence from nearby streams suggests that, in the absence of landslides/debris flows, woody debris may persist at least 50 to 100 years because flow in these small headwater channels is too small to transport large amounts of woody debris.

2.4.3. Abundance of fine woody debris

The number of FWD pieces in LS and YA streams was significantly smaller compared to all other systems (Table 2.3), while the difference between OG and YA ($p = 0.065$) was not significant. However, Sidle (1986) found that organic and small woody debris inputs were about twice as high as in old growth streams compared to young alder streams in southeast Alaska. Despite the significant regeneration of alder riparian stands in YA sites, numbers of FWD in LS and YA channels were not significantly different. The potential explanations of this result are: (1) deciduous FWD is broken and decomposed more rapidly compared to coniferous FWD (Harmon et al. 1986); and (2) fallen branches and stems from alder riparian stands of YA sites are smaller than FWD category. Thus, differences in abundance of FWD between YA and LS were not statistically apparent.

There is no significant difference in the numbers of FWD among CC, YC, and OG channels. However, Bilby and Ward (1991) observed that more fine organic debris occurred in old-growth streams than in clear-cut and young growth streams in Washington. In the Pacific Northwest, coniferous woody materials from old-growth forests have much slower decay rates than hardwood materials (Harmon et al. 1986). Thus, woody materials from coniferous old-growth stands accumulate and persist in stream channels.

Although the numbers of FWD pieces were not significantly different between OG and CC (Table 2.3), the recruitment of FWD in CC channels was largely related to logging activity (slash and small branches), while FWD in OG channels was attributed to natural inputs. Froehlich (1973) found logging slash to be a primary factor affecting FWD recruitment in headwater streams. A significant increase in FWD loading after clear cutting was also found in low gradient streams in southeast Alaska and western Oregon (Swanson et al. 1984). Large numbers of FWD also occurred in YC, even though much of this material was decayed and rotted. An old timber landing located just below the lowest reaches of YC3 contributed extensive FWD (400 pieces /100m). Numbers of FWD pieces in the upper and lower reaches of LS and YA varied widely; however, relatively small numbers of FWD were found in the upper reaches (Table 2.2).

2.4.4. Effects of landslides and debris flows on woody debris accumulations and distributions

The effects of landslides and debris flows on LWD can be assessed by comparing the two channels affected by these disturbances (LS and YA) with OG channels. Both total and in-channel numbers of LWD were not significantly different among OG, YA, and LS channels (Table 2.3). Although the landslides/debris flows transported LWD in the upper section of LS, some residue was found in and around stream channels. In YA, woody debris was also introduced from riparian stands in the intervening years after landslide activities. Thus, the numbers of LWD pieces among OG, YA, and LS were not statistically different. However, in-channel volumes of LWD in LS and YA channels were significantly smaller than volumes in OG streams because individual LWD pieces were relatively large and mature in OG systems (Table 2.3).

The number of LWD pieces in upper LS1 reach (15 total and 4 in-channel LWD pieces) was extremely low because this channel experienced two major landslide/debris flow events (1973 and 1993) compared to one event in 1993 in the other LS channels (Table 2.2 and Figure 2.6). Although two landslides and debris flows in 1961 and 1973 affected upper YA3, LWD levels were similar in all YA channels. These results indicate the importance of succession and recruitment of riparian alder into scour and runout zones of YA streams.

For both LS and YA, assessment of all organic components between upper and lower reaches yielded a significant treatment × channel gradient interaction. However, the average number of total (58.0 pieces) and in-channel (40.0 pieces) LWD per 100m in lower LS were relatively larger than numbers in upper LS (36.3 and 19.3 pieces). Similar tendencies were also found in YA channels (Table 2.2). The accumulation of LWD in the depositional zones of landslides and debris flows is common (Figure 2.4). Johnson et al. (2000) indicated that the amount of LWD accumulation in the deposition zones (i.e., debris fans) was largest in old-growth channels followed by second-growth and clear-cut channels. Because landslides in YA channels occurred 5 to 9 years after clear cutting, only logging residue and small-diameter standing trees were transported. In contrast, LWD transported by recent landslides and debris flows is associated with second-growth conifer riparian stands with mean diameters of 0.15 to 0.25 m. Therefore, much larger volumes of LWD were transported to lower LS reaches compared to lower YA reaches.

Stream gradient significantly influenced both in-channel and total numbers of LWD pieces (Table 2.3); gradient effects on numbers of FWD pieces were barely insignificant ($p = 0.065$). Correlations between numbers of LWD pieces (and also FWD) and channel gradient were conducted for all treatments including lower reaches of LS, YA, and CC. Correlations for LWD ($r = -0.53$, $p < 0.001$) and FWD ($r = -0.61$, $p < 0.001$) were significant only in upper LS. These negative correlations indicate that the number of woody debris pieces decreased with increasing stream gradient.

Numbers and volumes of LWD and FWD pieces were not significantly related to bankfull width (Table 2.3). In contrast to our results, Bilby and Ward (1989) found a negative correlation between channel bankfull width and LWD frequency in larger, lower gradient streams.

Our findings show that only landslides and debris flows modify the distribution of LWD and FWD with respect of gradient in headwater streams. In wider and lower gradient streams, woody debris distribution might be controlled the size of woody debris, flow regimes, bankfull width, and channel sinuosity (Bilby and Ward 1989; Robison and Beschta 1990; Nakamura and Swanson 1994). In such larger systems, stream size and flow regimes must be sufficient to transport LWD and FWD. However, bankfull widths and basin areas of headwater streams are generally too small to transport significant amounts of woody debris compared to fluvial processes in lower gradient channels. The distribution of woody debris in small streams is more likely affected by random factors such as bank erosion, tree mortality, wind throw, and logging slash (Berg et al. 1998). However, dynamic colluvial processes, such as landslides and debris flows, and intrinsic channel properties (i.e., gradient and channel smoothness) influence the distribution of woody debris in LS channels. Landslide channels typically have lower roughness than other systems; thus gradient breaks more strongly influence LWD and FWD accumulation in LS channels compared to channels with greater lateral and longitudinal roughness complexity.

2.4.5. The amount of sediment accumulation

Differences in sediment storage among the various stream types appeared to be masked by high variability among sites, especially in LS and CC channels (Figure 2.7). Although not significantly different (Table 2.4), average total volumes of sediment were considerably higher in LS and YA (5.35 and 4.75 m^3/100m, respectively) than in YC and OG channels (1.6 and 1.3 m^3/100m, respectively). Due to landslides and debris flows as well as subsequent sediment movement from hillslopes to channels, headwater streams in LS and YA were relatively sediment-rich. Active small bank failures contributed sediment transport in CC2.

The volume of sediment stored behind woody debris in YA channels was the significantly larger compared to OG, YC, and CC channels (Table 2.4). This increased storage in YA channels is attributed to the abundance of both sediment and woody debris due to past mass movements and subsequence riparian generation. For instance, in upper LS reaches, woody debris was a limiting factor because it was largely transported downstream by landslides and debris flows while sediment remained abundant. In contrast, sediment limited conditions and lower transport capacities induce smaller sediment accumulations behind woody debris (Berg et al. 1998). Rain splash, overland flow, shallow bank failures and freeze-thaw activity are the major erosive factors on disturbed slopes that recharge sediment into streams in LS channels. In the lower reaches of landslide channels, both sediment and woody debris are very abundant. Consequently, the role of woody debris in headwater streams changes depends on the "limiting" conditions of sediment and woody debris.

The sediment storage ratio in LS channels was significantly smaller than in other channels (Table 2.4). Riparian regeneration and recruitment of woody debris after landslides in YA significantly increased the sediment storage capacity of the channel. Although more sediment was generally observed in sites that were affected by landslides, a lower percentage of sediment in the channel was stored behind woody debris in LS streams. However, > 79% of total sediment was stored behind woody debris in YC, CC, and OG channels (Table 2.4; Figure 2.7). Similarly, 84% of sediment was stored behind logs, organic debris, roots, and stumps in steep streams in Idaho

(Megahan, 1982). In our study, FWD and FOD generally contributed less to sediment storage than LWD, but the amount of sediment stored behind FWD/FOD was the highest (28.7%) in OG channels (Figure 2.7). Total volume of sediment and sediment storage ratio between upper and lower sections of LS, YA, and CC were not significantly different. Out of the 702 LWD pieces that contributed to sediment storage, 53.7 % were oriented perpendicular (±45°) to the channels. However, only 37.9 % of all LWD pieces were oriented perpendicular (±45°) to channels. Thus, orientations that are nearly perpendicular highly influence sediment storage in all treatments.

2.4.6. Factors of sediment storage in headwater streams

Number of both LWD and FWD pieces significantly contributed to the volume of sediment stored behind woody debris (Table 2.4). Thus, a regression analysis was conducted for each treatment to predict volume of sediment stored behind woody debris using stream gradient, bankfull width, volume of LWD, number of LWD and FWD, and the accumulation of FOD as independent variables. The site variables were pooled in treatments to conduct the regression analysis. Multiple R-squared values ranged from 0.20 to 0.61 and from 0.23 to 0.74 in upper and lower reaches, respectively (Table 2.5). Multicolinearity occurred only between numbers of LWD pieces and volumes of LWD in the regression model for lower LS reaches ($r = 0.74$ and $p < 0.001$). In all treatments, stream gradient did not significantly influence the volume of sediment stored behind woody debris.

In OG channels, numbers of LWD and FWD pieces equally accounted for the volume of sediment stored behind woody debris (Table 2.5). The numbers of FWD pieces were significantly related to sediment storage in recent clear-cut sites (CC), while LWD numbers contributed strongly to sediment storage in YC. Recent logging slash provided initial sediment storage sites in CC channels. Because the stability of logging slash largely depends on channel bankfull width (Millard 2000), logging residue in narrow CC channels is relatively stable. After decomposition of these woody materials, sediment accumulations may gradually shift to LWD jams. In upper LS channels, numbers and volumes of LWD accounted for the bulk of sediment storage (Table 2.5). FWD clearly provided sites for sediment storage, whereas FOD was inversely correlated to sediment storage in upper YA channels (Table 2.5). Large accumulations of FOD behind woody debris dams in steep channels may occupy storage space and actually reduce the levels of sediment accumulation. Because of the recolonization of alder riparian stands after landslides and the interaction of these woody materials with stream channels, FWD contributed more to sediment storage in YA than in LS streams. Although Bilby and Ward (1989) found that FWD was more common in smaller streams, differences in riparian stand structure, such as between LS and YA, also influence the distribution and abundance of FWD. In the lower reaches of LS and YA, volume of LWD was significantly correlated to sediment storage (Table 5). In addition, with increasing numbers of LWD pieces and accumulations of FOD, sedimentation behind woody debris increases in the lower LS channels.

Our study indicates that different characteristics of woody debris accounted for sediment storage in the upper and lower sections of streams affected by landslides and debris flows. In the lower sections of LS and YA channels, LWD jams are common due to deposition of landslide/debris flow material. Thus, the volume of jams may modify the spatial distribution of sediment deposition. Bilby and Ward (1989) found that surface area of sediment deposition was significantly associated with the volume of woody debris in wider, low gradient forest streams in Washington. Lower gradient reaches have larger volumes of LWD pieces and jams and, thus, greater storage capacity behind LWD. On the other hand, high gradient headwater streams have limited storage space for sediment. Thus, higher numbers of LWD and FWD pieces (i.e., multiple dams) are more important for greater sediment storage in headwater streams (Figure 2.4). At the same time, some woody debris and sediment accumulations contribute to the formation of step structures in headwater channels. Such steps typically function to dissipate stream energy (Heede 1981). Size, interval, and stability of stepped-bed structures may critically affect sediment budgets and routing processes in headwater streams. The accumulation of sediment was controlled by different aspects of LWD in lower and upper reaches of landslide-affected channels as well as different types of woody debris resulting from of disturbances (logging activities and landslides/debris flows) and the recovery phase after such disturbances. Consequently, the dynamics of sediment in headwater streams might be greatly affected by the recruitment of woody debris due to logging and related disturbances.

2.5. Summary and conclusions

During the past decade, low gradient, fish-bearing streams in the Pacific Northwest have been managed to minimize the impacts of timber harvesting and other land uses on ecological and hydrological conditions of streams (Naiman et al. 2000). However, little attention has focused on regulating management activities around headwater streams, except for landslide and debris flow hazard mitigation. This may be attributed to the lack of understanding of the complete interactions between woody debris and sediment in headwater streams. Thus, the dynamics of headwater streams and their impacts on downstream resources are poorly understood, even though the headwater streams are primary sources of organic materials, nutrients, and sediments. Moreover, headwater streams often flow directly though timber harvest units. We found that timber harvesting and related landslides/debris flows affected the distribution and accumulation of woody debris and related sediment accumulation in headwater streams (Figure 2.8). These effects are summarized as: (1) inputs of logging slash and unmerchantible logs significantly increase the abundance of in-channel woody debris; (2) in the absence of landslide/debris flows, these woody materials remain in the channel 50 to 100 years after logging; (3) relatively smaller woody debris initially stores sediment; (4) when landslides and debris flows occur 3 to 15 years after logging due to intensive rain and weakening of root strength (Sidle et al. 1985), woody debris is evacuated from headwater streams and deposited in downstream reaches; (5) although less woody debris remains in the scour zone, woody debris pieces and jams contribute to sediment storage in both the scour and deposition zones of landslide/debris flow channels; (6) red alder stands actively re-colonize riparian zones of headwater streams for 20 to 50 years after mass movement and recruit woody debris and organic materials which in turn provide sediment storage sites; and (7) subsequent sediment movement after landslides/debris flows is affected by residual woody debris and newly introduced debris.

The disturbance regime, both natural and management-related, significantly affected headwater ecosystems. Three aspects of disturbances appear important for understanding the functions of headwater streams: (1) logging slash; (2) landslides/debris flows; and (3) regeneration of riparian stands after logging and mass movement. Such conditional changes with time affect abundance and distribution of LWD, FWD, and sediment (Figure 2.8). Moreover, these modifications determine the in-stream function of LWD and FWD, particularly related to sediment storage. Thus, the dynamics of sediment movement as well as stream channel geomorphology in headwater streams may relate to such management/disturbance regimes through time and space. Both episodic and chronic events are important for understanding the dynamics of headwater streams and to evaluate downstream impacts.

Forest practices in and around headwater streams are inconsistently regulated and management is based on very limited scientific knowledge. For instance, steep headwater streams without salmonids do not typically require riparian buffer zones. Even when riparian buffer strips are left, the relatively narrow riparian corridor may be highly susceptible to wind throw. Wide riparian buffers in headwater systems will reduce the amount of timber available for harvest. To effectively manage headwater streams, information on geomorphic processes, hydrology, and riparian vegetation dynamics needs to be systematically integrated.

Table 2.1 Characteristics of the study sites.

	Drainage area (Km^2)	Length of studied channel (m)	Average gradient (%)	Average bankfull width (m)	Bedrock (%)	D_{50} (mm)	Landslides and Debris flows
LS1* Upper	0.21	340	40.3 (11.0)	1.2 (0.6)	26.7	30	1993/1979
Lower		400	9.9 (5.8)	2.6 (1.5)	0.0	25	
LS2* Upper	0.27	150	31.0 (12.3)	1.6 (0.4)	40.7	31	1993
Lower		250	13.7 (6.0)	1.8 (0.6)	0.0	30	
LS3* Upper	0.35	300	31.7 (11.5)	2.8 (1.3)	59.8	43	1993
Lower		350	9.4 (8.1)	3.7 (1.3)	0.0	29	
YA1* Upper	0.22	125	36.6 (9.3)	1.1 (0.5)	26.0	36	1961
Lower		100	17.5 (6.8)	1.4 (0.5)	2.0	35	
YA2*Upper	0.14	225	42.7 (9.1)	0.9 (0.3)	38.0	40	1961
Lower		125	18.6 (7.1)	0.9 (0.3)	0.0	27	
YA3* Upper	0.21	150	28.9 (11.2)	2.0 (0.6)	47.1	38	1979/1961
Lower		300	17.4 (7.3)	1.9 (0.6)	0.0	28	
YC1	0.24	300	23.8 (5.7)	1.2 (0.4)	0.0	28	
YC2	0.12	100	43.0 (11.5)	0.6 (0.4)	0.0	40	
YC3	0.26	250	25.8 (7.3)	1.9 (1.0)	21.9	33	
CC1**Upper	0.20	200	44.4 (6.4)	0.9 (0.4)	0.0	48	
Lower		190	25.5 (8.2)	1.0 (0.4)	0.1	30	
CC2**Upper	0.20	130	45.9 (6.2)	0.9 (0.5)	0.1	40	
Lower		150	32.5 (12.7)	0.9 (0.4)	0.0	19	
CC3	0.19	225	39.8 (7.6)	1.3 (0.7)	0.0	38	
OG1	0.19	150	40.9 (11.7)	0.8 (0.4)	13.4	62	
OG2	0.22	150	45.0 (8.7)	1.6 (1.1)	26.9	50	
OG3	0.25	200	8.5 (4.1)	1.9 (0.6)	0.1	37	

Note: LS, recent landslide (landslide and debris flows in 1979 and (or) 1993); YA, young alder riparian forest (logged from 1953 to 1957 and landslide and debris flows in 1961 and (or) 1979; YC, young conifer riparian forest (logged from 1959 to 1961); CC, clear cut (logged in 1995); OG, old-growth sites.

Standard deviations (SD) are expressed in parentheses.

* Sites are divided into scour or run-out (upper section) and deposition (lower section) zones of landslides and debris flows.

** Sites are divided into upper and lower reaches at logging roads.

Table 2.2 The characteristics of woody debris

	Large woody debris							Number of FWD (/100m)
	Number (/100m)		Mean Diameter (m)	Median Diameter (m)	Mean Total length (m)	Median Total length (m)	Total volume per pieces (m^3)	
	Total	In-channel						
LS1 Upper	15	4	0.19 (0.15)	0.15	5.2 (4.0)	5.5	0.2 (0.3)	15
Lower	40	29	0.24 (0.17)	0.19	2.2 (2.2)	1.4	0.3 (1.0)	106
LS2 Upper	37	27	0.18 (0.08)	0.15	1.4 (0.8)	1.0	0.1 (0.1)	67
Lower	54	45	0.22 (0.15)	0.17	1.9 (1.8)	1.4	0.2 (0.4)	71
LS3 Upper	57	27	0.19 (0.12)	0.16	2.1 (1.8)	1.5	0.2 (0.2)	53
Lower	80	46	0.28 (0.27)	0.19	3.1 (2.6)	2.0	0.6 (3.3)	116
YA1 Upper	24	21	0.20 (0.15)	0.16	2.2 (1.7)	1.7	0.2 (0.4)	41
Lower	52	37	0.22 (0.16)	0.17	1.4 (0.9)	1.1	0.1 (0.2)	82
YA2 Upper	20	16	0.19 (0.08)	0.17	3.8 (3.5)	2.5	0.1 (0.1)	55
Lower	14	14	0.24 (0.19)	0.13	1.9 (1.8)	1.1	0.2 (0.4)	48
YA3 Upper	29	23	0.25 (0.15)	0.20	3.1 (3.4)	1.9	0.2 (0.3)	27
Lower	66	59	0.23 (0.14)	0.19	1.7 (1.3)	1.3	0.2 (0.6)	105
YC1	52	34	0.26 (0.18)	0.20	3.3 (3.3)	2.5	0.5 (3.5)	130
YC2	80	35	0.30 (0.15)	0.25	5.0 (3.1)	4.8	0.5 (0.7)	102
YC3	116	66	0.30 (0.20)	0.25	3.0 (2.4)	2.3	0.5 (1.5)	399
CC1 Upper	78	58	0.22 (0.15)	0.16	2.7 (1.9)	2.0	0.2 (0.4)	163
Lower	55	34	0.23 (0.17)	0.16	2.5 (2.0)	1.6	0.3 (0.8)	124
CC2 Upper	42	25	0.20 (0.13)	0.17	2.6 (2.0)	2.0	0.2 (0.4)	110
Lower	62	39	0.20 (0.10)	0.16	2.7 (1.9)	2.0	0.1 (0.2)	99
CC3	82	65	0.23 (0.15)	0.17	1.6 (0.9)	2.0	0.2 (0.4)	151
OG1	31	21	0.24 (0.13)	0.20	4.0 (3.8)	2.5	0.3 (0.7)	124
OG2	41	24	0.37 (0.26)	0.26	4.6 (4.1)	2.7	1.1 (2.5)	143
OG3	52	33	0.25 (0.19)	0.19	3.1 (2.5)	2.2	0.4 (1.1)	150

Note: See Table 1 for definition of the treatment code
* Standard deviations are shown in parentheses

Table 2.3 Summary of mixed effect ANCOVA on the number and volume of woody debris in upper sections

		Treatment	Stream gradient	Bankfull width	Multiple comparisons and means
Number of in-channel LWD (/20m)	F p-value	4.99 ***0.019***	5.32 ***0.026***	0.01 0.930	LS (3.6), YA (4.0), OG (5.1) << YC (9.3), CC (10.9)
Total number of LWD (/20m)	F p-value	4.35 ***0.028***	6.79 ***0.012***	1.44 0.23	YA (5.0), LS (6.8) << CC (14.4), YC (16.1) OG (8.3) << CC
In-channel volume of LWD (m^3/20m)	F p-value	2.55 0.104	0.02 0.886	0.04 0.845	
Total volume of LWD (m^3/20m)	F p-value	7.27 ***0.005***	0.66 0.419	1,36 0.419	LS (0.6) << CC (0.27), OG (5.8), YC (8.2) YA (0.8) << OG, YC
Number of FWD (/20m)	F p-value	4.01 ***0.035***	3.57 0.065	0.45 0.506	LS (8.1) << OG (28.4), CC (29.5), YC (46.0) YA (9.3) << CC, YC

Note: Multiple comparisons with Bonferroni method were conducted at the 0.05 of confidence level. Treatment × channel gradient and Treatment × bankfull width were not significant. See Table 1 for definitions of the treatment codes.
d). The order in percentiles from left to right shows the relative abundance (smaller abundance in left side). Values in parentheses are mean numbers. Treatment separated by << symbols are significant different.

Table 2.4 Summary of mixed effect ANCOVA for sediment accumulation and sediment storage behind woody debris in upper sections. Multiple comparisons with Bonferroni method were conducted at the 0.05 of confidence level (<< shows significant difference).

		Treatment	Stream gradient	Bankfull width	Number of LWD	In-channel volume of LWD	Number of FWD	FOD	Multiple comparison And mean
Volume of total sediment (m^3/20m)	F p-value	2.79 0.085	0.36 0.551	2.35 0.130	0.23 0.631	0.49 0.485	0.82 0.366		
Volume of sediment storage Behind woody debris (m^3/20m)	F p-value	4.04 ***0.009***	0.07 0.796	0.91 0.344	13.0 ***0.001***	2.12 0.149	12.9 ***0.001***	0.54 0.462	(OG, YC, CC) << YA (0.24, 0.37, 0.49) << 0.60 no differences in LS
Sediment storage ratio per 20m	F p-value	6.96 ***0.003***	0.10 0.750	2.11 0.152	4.28 ***0.041***	4.03 ***0.047***	0.01 0.937		LS << (YA , OG, YC, CC) 0.22 << (0 .55, 0.79, 0.82, 0.88)

* Parentheses below the rank of treatment show average numbers
* Significant p-value is italicized and bolded
* No interaction term was significant.

Table 2.5 Summary of stepwise regression analysis to predict volume of sediment stored behind woody debris (SW).

Treatment	Equation	
Upper reach		
LS	SW = 0.79 LWD +2.20 Volume - 2.4446	R^2 = 0.56, n = 26, F = 15.22, p < 0.001
YA	SW = 0.67 FWD – 0.68 FOD – 0.83	R^2 = 0.40, n= 23, F = 6.9, p = 0.005
YC	SW = 0.27 LWD – 0.08	R^2 = 0.32, n= 31, F = 14.4, p < 0.001
CC	SW = 0.19 FWD + 0.03	R^2 = 0.20, n= 26, F = 6.1, p = 0.021
OG	SW = 0.10 LWD + 0.10 FWD – 0.10	R^2 = 0.61, n= 23, F = 16.6, p < 0.001
Lower reach		
LS	SW = 0.20 LWD + 0.56 Volume + 0.13 FOD + 0.03	R^2 = 0.74, n= 68, F = 62.5, p < 0.001
YA	SW = 1.24 Volume –0.51 Width+0.74	R^2 = 0.46, n= 48, F = 19.9, p < 0.001
CC	SW = 0.28 FWD – 0.18	R^2 = 0.23, n= 30, F = 8.9, p < 0.006

Note: Relationship between the volume of sediment behind woody debris (SW) and the other variables (BW: Bankfull width, S: slope, LWD: number of LWD, FWD: number of FWD, Volume: volume of LWD, FOD: accumulation of FOD) are selected using a stepwise procedure with Cp statistics. All variables were transformed using log (x+1) prior to regression analysis. The null hypotheses, (H_0) is that coefficients of variables are equal to 0, are all rejected at 0.05 level except intercepts. See Table 1 for definition of the treatment codes.

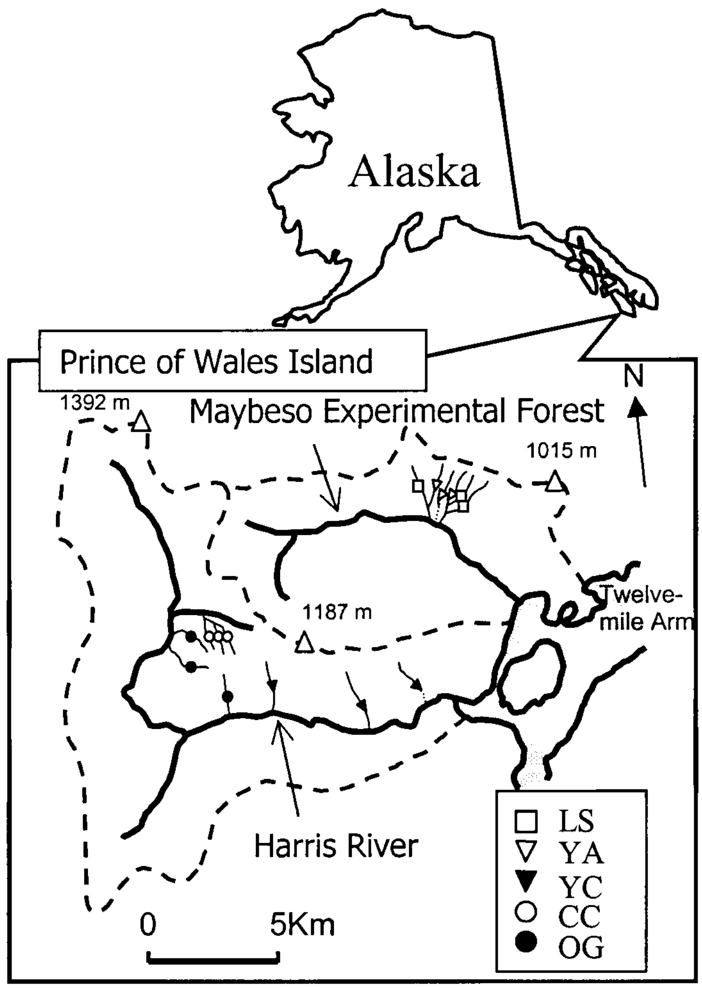
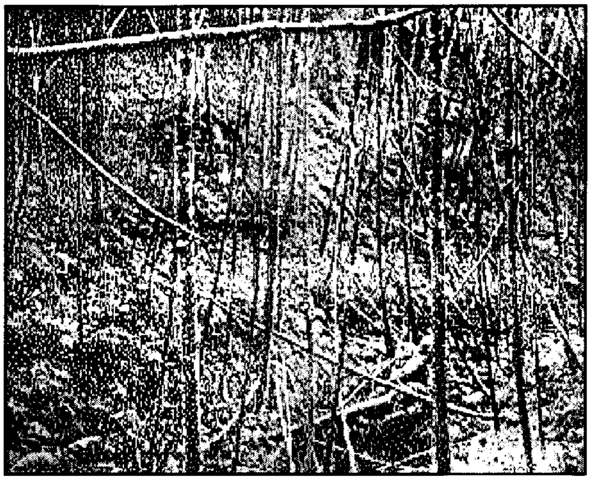


Figure 2.1 Location of study sites in headwater streams of Maybeso Experimental Forest and the Harris river basin. Broken line shows watershed boundary. See Table 1 for definition of the treatment codes.

LS1

LS3



YA3

Figure 2.2 Examples of study streams in Landslide (LS) and Young alder (YA). Less woody debris pieces and exposed bedrock were observed in the LS channels. Thin and dense young alder stands covered riparian zones of the YA channels.

YC3

CC2

OG2

Figure 2.3 Examples of study streams in Young conifer (YA), Clear cut (CC) and Old-growth (OG). Dense second growth conifer stands covered riparian zones of the YC channels. No riparian over story vegetation was found in the CC channels. No mass movement and timber harvesting was occurred in CC channels for at least the last 100 years.

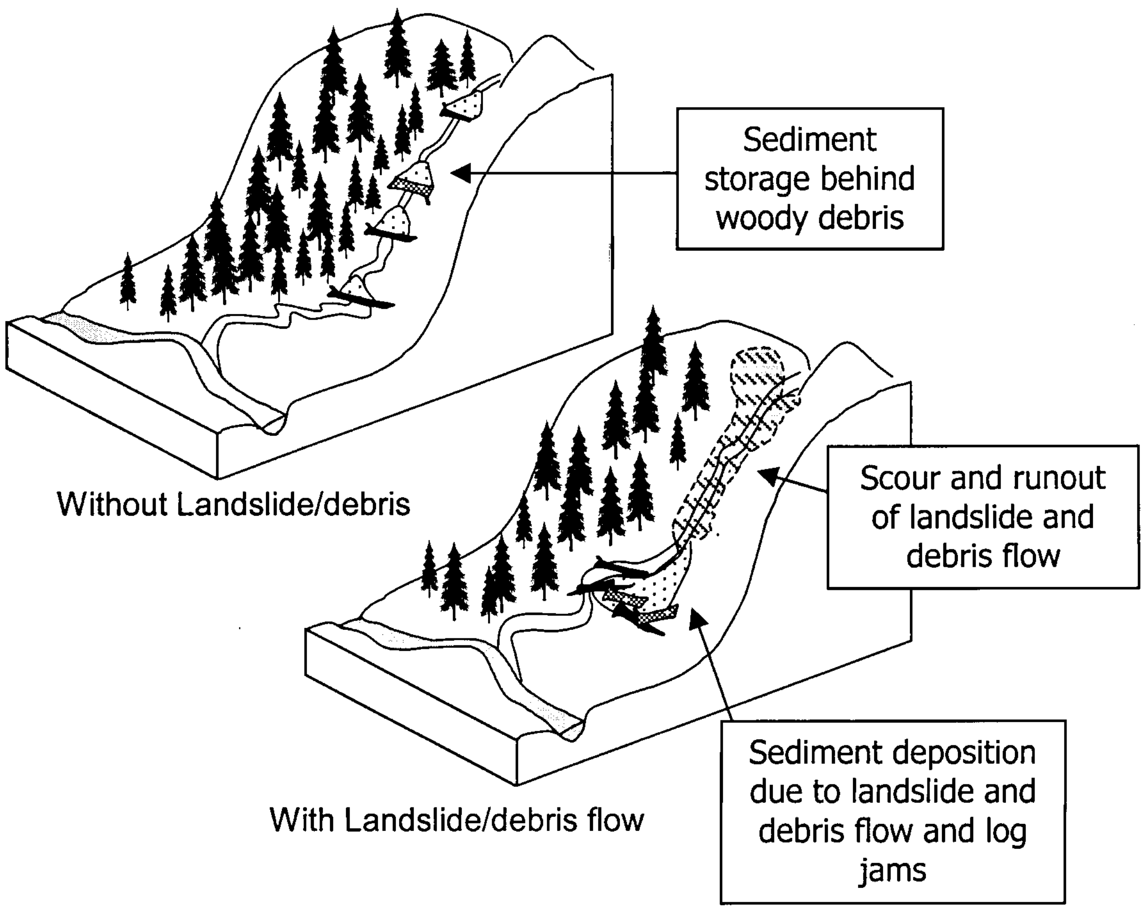


Figure 2.4 Schematic view of headwater streams with and without landslides and debris flows. Sediment stored behind woody debris is distributed along stream channels in headwater streams without landslides and debris flows. The accumulation of sediment and woody debris occurs in the deposition zones after landslides and debris flows. The terminal end of deposition dose not reach a main channel because of the wide and flat bottom of U-shaped glacial valley.

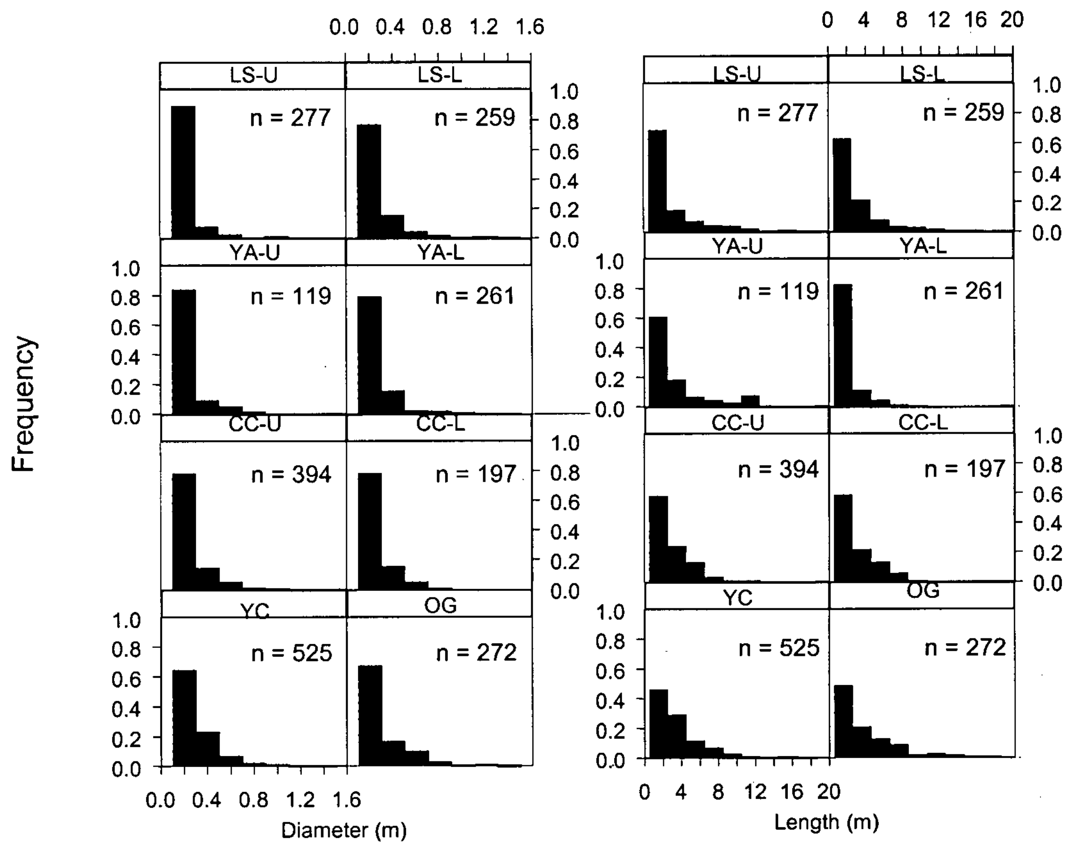


Figure 2.5 Distribution of diameter and length of large woody debris. L and U, upper and lower sections in LS and YA channels, respectively.

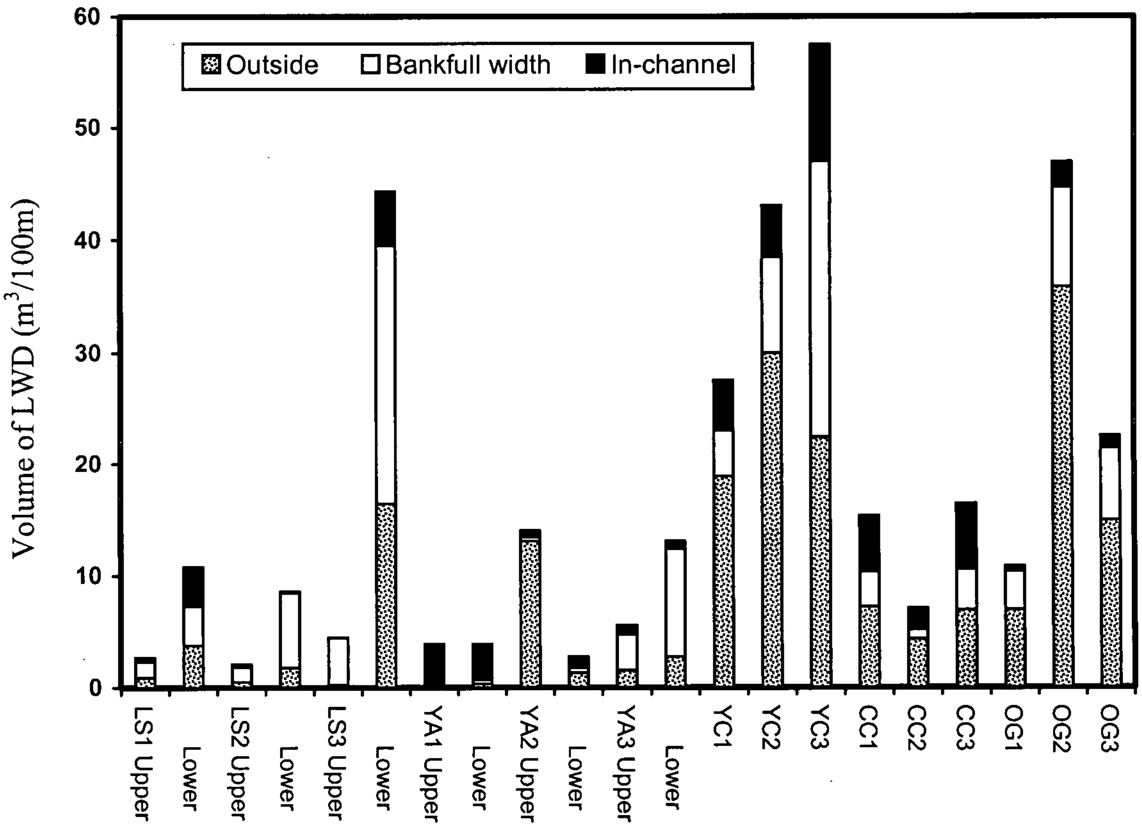


Figure 2.6 Volume of LWD in and around streams. In channel: the volume of LWD located within the wetted channel width that significantly affects flow dissipation and sediment transport. Bankfull: the volume of LWD located within the bankfull width, which was defined by the absence of vegetation. Outside: the volume of the terrestrial portion of LWD located outside of the bankfull width. See Table 1 for definition of the treatment codes.

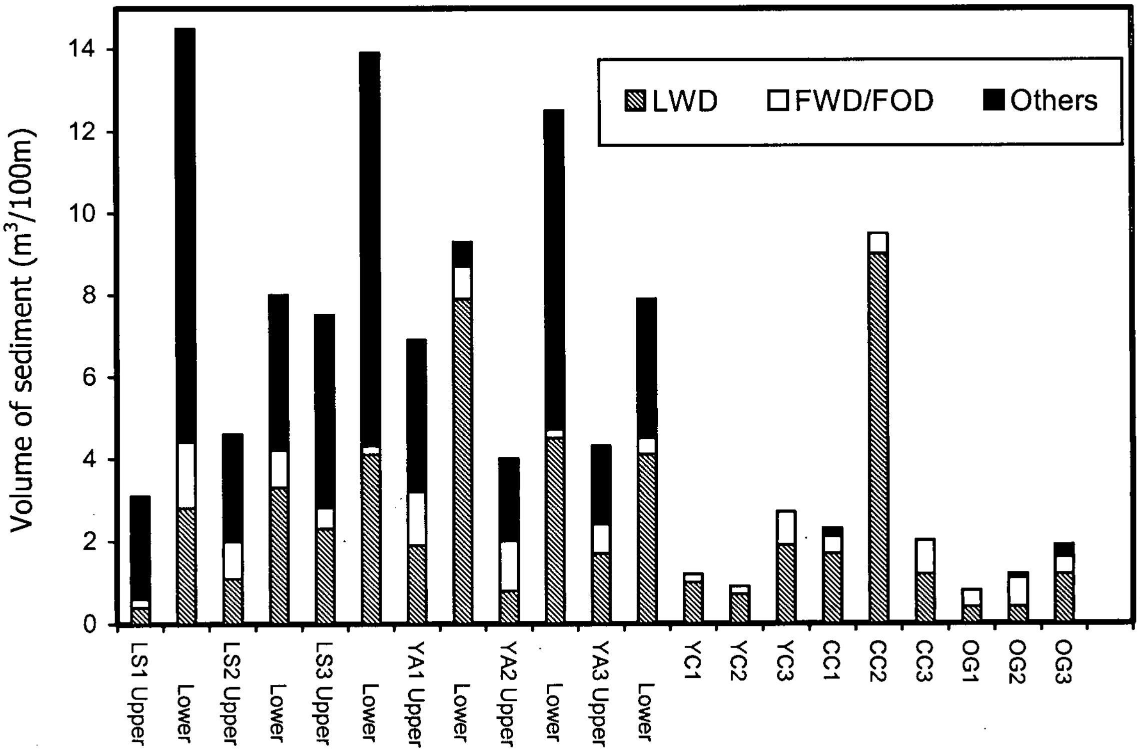


Figure 2.7 Volume of sediment behind woody debris, and the other obstructions. LWD: large woody debris formed sediment storage. FWD-FOD: fine woody debris and fine organic debris formed sediment storage. Other: rock and bedrock formed sediment storage. See Table 1 for definition of the treatment code.

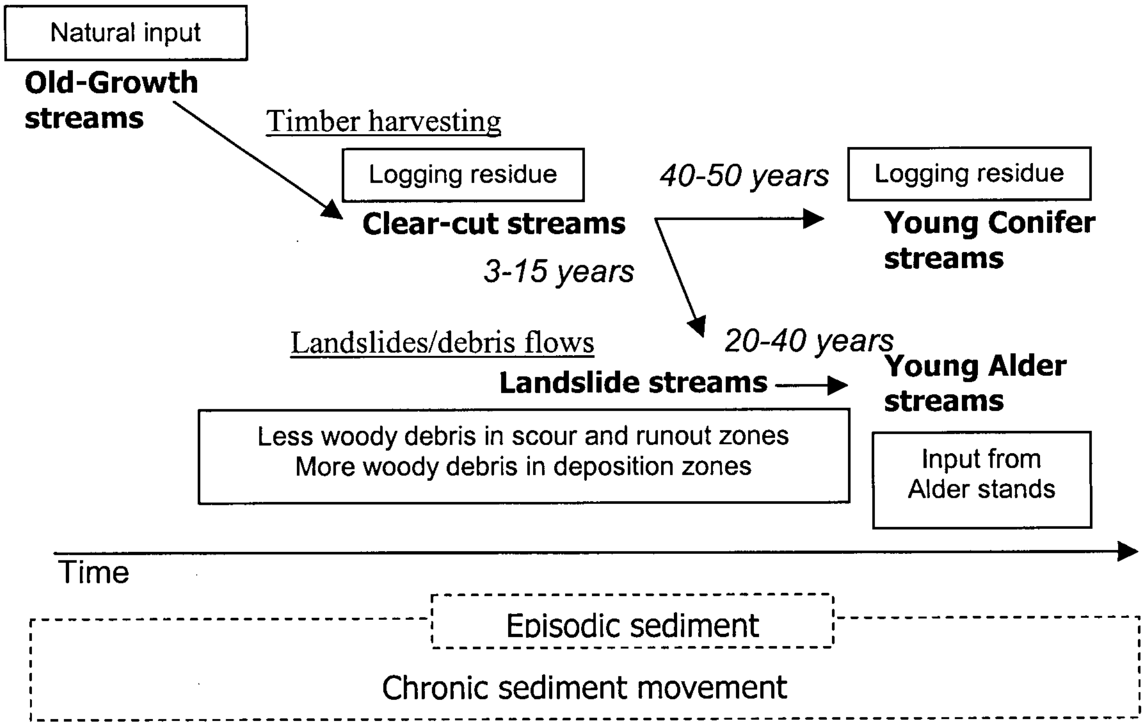


Figure 2.8 Flow charts of woody debris and sediment accumulation in headwater streams. Examination of five management and disturbance regimes in this study (OG, CC, YC, YA, and LS) shows the changes of recruitment of woody debris and sediment storage in headwater streams along the time axis. Solid rectangles show the major recruitment modes of woody debris in each treatment. Rectangles with broken lines show types of sediment movement. Such changes due to management and disturbance are typically seen in landscape of southeast Alaska.

Chapter 3

Characteristics of channel steps and reach morphology

3.1. Introduction

Because headwater channels are confined by hillslopes, variations of longitudinal profiles such as vertical drops and pools modify complexity of stream channels as contrasted to the greater lateral variability in downstream reaches. Therefore, channel steps, which are staircase-like in appearance and formed by boulders and logs, represent significant channel units in headwater streams with channel gradient > 0.05 (e.g., Ashida et al., 1985; Chin, 1989; Grant et al., 1990; Zimmerman and Church, 2001). Channel steps can be found in biogeoclimatic conditions ranging from arid deserts (Wohl and Grodeck, 1994) to humid forests (Heede, 1972). Steps in step-pool channels are formed under relatively low sediment supply conditions (Grant et al., 1990; Montgomery and Buffington, 1997) during infrequent flood events (20- to 100-yr recurrence intervals; Chin, 1997). Church (1996) documented that the interlocking channel bed structures of boulders and cobbles generate stability in step-pool channels. Maita (1996) reported that passing sediment wave through step-pool channel destroyed and rearranged steps in a headwater channel. Bedrock steps typically occur in bedrock-exposed reaches subject to higher sediment transport events (e.g., flash floods and mass movement) (Wohl, 2000; Duckson and Duckson, 2001). Sequences of steps and pools alter the transport of bed load sediment in headwater channels, because they wedge, jam, and store material (Whittaker, 1987).

Single and multiple pieces of woody debris contribute to the formation of channel steps in forested streams because woody debris controls local flow direction and channel roughness, impounds sediment (Heede, 1972; Woodsmith and Swanson, 1997). Woody debris and log jams alter the longitudinal profiles of channels by forming steps and pools and modify channel sinuosity and side channels in low gradient channels (Nakamura and Swanson, 1993). Woody debris typically stores sediment and alters substrate composition (Smith et al., 1993). Structure and abundance of channel steps affect biological processes in headwater streams because channel steps modify flow velocity, substrate type, and geometry of pools. Organic materials are often stored behind woody debris and boulder dams (Bilby and Likens, 1980). Retention of organic material due to in-channel obstructions alters community structure and abundance of macroinvertebrates – this in turns modifies decomposition processes of organic materials (Wallace et al., 1995).

Because timber harvesting and mass movement alter channel and riparian conditions in forested headwater streams (Sidle et al., 1985), amount and distribution of woody debris and sediment in headwater channels are modified with the onset of timber harvesting and mass movement as well as the recovery processes (Gomi et al., 2001). Amount of woody debris in headwater streams significantly increases after timber harvesting due to the recruitment of logging debris (Swanson et al., 1984, Millard, 2000). Such woody debris remained in channels 40 years after logging (Gomi et al., 2001). Number of woody debris pieces significantly decreased in scour and runout zones of landslides and debris flows, because woody debris was transported to the deposition zones. Once alder regenerated in riparian zones woody debris in these channels gradually increased (Gomi et al., 2001). Such changes in timing and types of woody debris inputs and their influence on local hydraulic conditions and sedimentation are expected to affect reach morphology and the distribution of channel steps in headwaters.

Changes in the amount and size of woody debris due timber harvesting and mass movement directly may alter channel morphology such as channel steps, pools, and channel reach types in headwater streams (Woodsmith and Buffington, 1996; Rot et al., 2000). Two years after experimental deforestation, numbers of woody debris dams decreased and subsequently sediment transport increased in Hubbard Brook Experimental Forest, NH, USA (Hedin et al., 1988). Experimental removal of woody debris in a forested channel in SE Alaska increased bed load transport (Smith et al., 1993). In contrast, experimental installation of woody debris created channel steps by trapping bed load (Wallace et al., 1995). Changes in amount or volume of woody debris may modify channel reach types. For instance, decreasing the amount of woody debris in stream channels can lead to a shift from forced step-pool and forced pool-riffle to bedrock and plane-bed reaches, respectively (Montgomery and Buffington, 1998). Mass movement created bedrock reaches in scour and runout zones (Montgomery and Buffington, 1997). However, recruitment of woody debris changes the distributions of bedrock and alluvial reaches depended on sediment accumulation behind the log jams (Montgomery et al., 1996).

Because of the close coupling between hillslopes and channels as well as terrestrial and aquatic environments in headwater systems, the history of timber harvesting and mass movement related to abundance of woody debris and sediment alter hydrogeomorphic processes and channel morphology at various spatial and temporal scales (Sidle, 2000). To understand the geomorphic responses of headwater channels to external influences such as mass movement and timber harvesting, and the complex processes which produce them, we investigated channel steps and reach morphology. The objectives of this study are to (i) describe the structure and geometry of channel steps formed by woody debris, boulders, and bedrock among different management and disturbance regimes; (ii) examine the distribution and types of channel reaches related to channel steps; and (iii) evaluate the effects of timber harvesting and mass movement regimes on channel steps and reach morphology. In this study, channel steps formed by both fluvial and colluvial processes were investigated.

3.2. Study site

This study was conducted in the Maybeso Experimental Forest and the adjacent Harris River basin in the Tongass National Forest, Prince of Wales Island, SE Alaska (Figure 3.1). The climate in this area is cool and temperate. Mean annual temperature is 10°C and mean annual precipitation is 2800 mm. The basins are U-shaped glacial valleys covered by varying thickness of glacial till. Dominant forest vegetation includes western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*), and red alder (*Alnus rubra*); however, riparian vegetation is highly influenced by past mass movement regimes such as landslides and debris flows. Maybeso Valley was initially logged in 1953 and logging continued until 1957. Timber harvesting was conducted from 1959 to 1961 in the Harris River basin. More recent clear-cutting occurred in the

Harris River basin in 1995 in relatively smaller cut-blocks. All harvesting units were clear-cut using cable yarding methods on hillslopes. For both recent and past logging activities, logging slash was neither removed from stream channels nor burned on-site after timber harvesting.

Five types of streams (i.e., 'treatments') that reflect the history of timber harvesting and mass movement in riparian zones of headwater channels were identified within the Maybeso Experimental Forest and the Harris River basin (Figure 3.1). The five treatments, identified as OG, CC, YC, YA, and LS, were described based on the dominant riparian stands (species and age). Riparian zones in old-growth (OG) streams had pristine and mature conifer stands dominated by western hemlock and red cedar. No riparian overstory vegetation existed along recent (≤ 3-yr old) clear-cut (CC) channels. Because of logging activities in 1957, young conifer (YC) stands of western hemlock and Sitka spruce dominated in riparian zones. In sites clear-cut during the same period, but which experienced landslides and debris flows in 1962 and (or) 1979, young-growth alder (YA) dominated the riparian zones of headwater streams. Because of recent (1993) landslides and debris flows, unvegetated scour and deposition zones along with immature (mean diameter 0.03 m and height 2 m) alder stands were observed in the riparian zone certain channels (LS). Details of these disturbance regimes are presented by Gomi et al. (2001) and summarized in Table1. Resident cutthroat trout (*Oncorhynchus clarki*) and Dolly varden (*Salvelinus malma*) were observed in the study steams with the exception of the steep upper reaches.

Three headwater streams were examined in each of four headwater channel types (LS, YA, YC, and CC); four streams were selected in OG channels. Aside from the 'external' timber harvesting and mass movement influences, streams within treatments were selected based on relatively uniform bankfull widths and gradients among streams, channel continuity from upper to lower reaches, and perennial flows. Drainage area of the 16 streams ranged from 0.12 to 0.35 km^2 (Table 3.1). The entire drainage basins including hillslopes, zero-order basins, and stream channels in LS, YA, YC, and OG represented the designated treatment types. In the CC treatments, approximately the upper 15% of the channel was in old- growth forest due to the smaller cut-block size; this undisturbed reach was excluded from the survey to identify the characteristics of CC channels.

To evaluate the influence of landslides and debris flows on the channel morphology and woody debris distribution, both LS and YA streams were divided into upper (scour and runout) and lower (deposition) sections based on field observations (see Figure 3.2 in Gomi et al., 2001). All landslides typically mobilized into channelized debris flows that deposited sediment in lower gradient reaches in LS and YA channels. Debris flows transported sediment and woody debris and formed log jams in the deposition zones on the valley floor. The lower ends of the deposition zones did not reach the main channel of Maybeso Creek due to the wide, flat valley bottom. No evidence of recent mass movement such as scour or deposition was found in and around YC, CC, and OG streams. Although a logging road crossed two CC channels, the effect of the road on the abundance of woody debris and sediment was not statistically significant (Gomi et al., 2001).

The length of the surveyed headwaters varied from 100 to 400 m among stream types. If channel profiles and distribution of woody debris and sediment were relatively uniform in the entire headwater channels (e.g., YC, CC, and OG), shorter reaches (minimum 100 m) were surveyed. We thus assume that survey sections represent geomorphic characteristics in these streams. In contrast, distribution of woody debris and sediment as well as channel morphology was measured in longer sections of LS and YA channels. These longer surveys included zones of scour, runout, and deposition related to mass movement in the upper and lower reaches of LS and YA, to capture the up- to downstream transport of sediment and woody debris. Mean channel gradient ranged from 0.09 to 0.45, and mean bankfull width ranged from 0.6 to 3.7 m (Table 3.1). Elevations from lower to upper ends of the study streams ranged from 80 to 270 m in YA and LS; in YC, CC, and OG elevations ranged from 150 to 330 m.

3.3. Methodology

Field methods

Fifteen streams, 100 to 400 m in length, were intensively surveyed during the period from June to August 1998. An additional OG channel was surveyed in July 1999, as it was selected for monitoring bed load and suspended movement. Stream gradients were surveyed using an engineer's level, stadia rod, and tapes along the centerline of the channels. Stream elevation was measured at 5-m intervals and at any steps ≥ 0.1 m of vertical height that spanned the channel. For example the upper and lower boundaries of log, boulder, and bedrock steps were surveyed. Exposed bedrock length and its position in the channels were measured. The wetted and bankfull width of the stream was measured every 5 m. Bankfull width was defined by the presence of moss and rooted vegetation along the channel margins and the top of the banks. Riparian stand structure was measured in 10×10 m plots along the stream edge for each 50-m reach; plot positions – both longitudinal and left/right side of channel – were randomly selected for each 50-m reach. All live trees ≥ 0.1 m diameter at breast height (DBH) were tallied and the species composition was documented.

Headwater streams were categorized in three hierarchical levels: headwater segment, channel reach, and channel unit (Frissell et al., 1986). A *headwater segment* is an entire headwater channel typically, 100 to 1000 m in length. A *channel reach* exhibits a more homogenous pattern of channel bed form over a defined stream length. Relatively uniform hydrologic and geomorphic processes govern within channel reaches (Frissell et al., 1986). A *channel unit* is a subsystem of a channel reach varying from 1 to 10 m in length (up to several channel widths in length) (Montgomery and Buffington, 1998). While pools and riffles are the major channel units in low gradient channels, channel steps dominate in headwater streams (Chin, 1989). This study particularly focuses on channel reach morphology and channel steps in headwater streams.

For channel steps, height and interval length were measured. Step heights were estimated as the vertical distance between the top and bottom of slope breaks higher than 0.1 m. Step interval length was the calculated distance between the tops of steps parallel to mean channel gradient (Figure 3.2). Because local channel gradient and bankfull width are related to the step geometry (e.g., Chartrand and Whiting, 2000), mean channel gradient and bankfull width were calculated for consecutive 20-m reaches. A 20-m reach length was deemed suitable to characterize step morphology. The organic debris that contributes to formation of steps was divided into woody debris and fine organic debris (FOD). FOD was typically an accumulation of leaves and small branches. Woody debris was further categorized as (i) large woody debris (LWD) with pieces ≥ 0.5 m in length and ≥ 0.1 m in diameter and (ii) fine woody debris (FWD) with pieces ≥ 0.5 m in length and 0.03 to 0.1 m in diameter. Channel steps were then classified as LWD, FWD, FOD, boulder, and bedrock steps based on the primary forming element of each step.

To quantify the characteristics of LWD, the following properties were measured: in-channel, bankfull and total lengths, diameter, longitudinal position, and orientation. In-channel length was defined as the portion of the LWD piece located within the wetted channel for low flow conditions. Bankfull length was defined as the portion of LWD pieces within bankfull width. Total lengths were measured for entire pieces of LWD including terrestrial portions. The diameter at the middle of each piece of woody debris (within bankfull length) was recorded. In-channel and bankfull volume components of LWD (m^3: V) were calculated as follows:

$$V = \pi \times (D/2)^2 \times L \qquad [1]$$

where *D* and *L* are the diameter and appropriate length, respectively. Orientation of LWD was measured related to a line parallel to the channel axis to determine the degree of interaction of LWD pieces with the stream. Both left- (+) and right- (-) hand orientation of LWD from 0° to 90° were recorded within $\pm 5°$ intervals. FWD was surveyed with respect to channel position and number of pieces. Volumes of FOD were categorized as small (< 0.01 m^3), medium (0.01 to 0.1 m^3), and large (≥ 0.1 m^3), where FOD accumulations contributed to and/or formed a sediment wedge.

Consecutive 20-m reaches were classified into the following types based on field observations and survey data: bedrock, cascades, step-pools, step-steps, rapids, and pool-riffles (Table 3.2; Figure 3.2). Instead of morphologic brakes, we employed fixed 20 m reaches (approximately 10 times bankfull width: Frissell et al., 1986) to conduct statistical analyses for number and distribution of channel reach types among treatments. The dominant reach type was selected if several reach types were mixed within 20 m reaches. Characteristics of bedrock, cascade, step-pool, and pool-riffle reaches were based on the classification of Montgomery and Buffington (1997) (Table 3.2). The term "rapids" (introduced by Zimmerman and Church (2001)) was used to avoid confusion arising from the established use of the term "plane-bed" (Montgomery and Buffungton, 1997) (Table 3.2; Figure 3.2). One notable variation in this paper from the typologies of Montgomery and Buffington (1997) and Zimmerman and Church (2001), is the term "step-step" used to explain a varataion of step pools; we hypothesis increases woody debris and sediment alter step interval and pool depth. In step-step reaches, channel steps formed by boulders and logs are geometrically organized and span channels; however, defined pools are not formed between steps. Similar to step-pools defined by Montgomery and Buffington (1997), materials at the bottom steps in step-step reaches are sorted and are finer than step forming materials. In cascade reaches, however, step-forming materials are relatively disorganized and materials at the bottom steps are not finer; this is critical for distinguishing between cascades and step-step reaches (Table 3.2; Figure 3.2).

Statistical methods

Three levels of hierarchical structure were included in the statistical analysis: treatment, individual streams within treatment, and 20-m consecutive reaches within individual streams. It was not possible to randomly sample streams in the study landscape because treatments were dictated by external geomorphic factors (i.e., upper and lower reaches of YA and LS), management effects (i.e., YC and CC) and natural conditions (i.e., OG). Therefore, a mixed-effect procedure was used to assess the treatment effect. A fixed model of treatment effects was employed in this observational study (LS, YA, YC, CC, and OG), while streams within treatment (1, 2, 3, and 4) were considered to be random factors. Consecutive 20-m reaches from all 16 streams were included. Because consecutive 20-m reaches might be correlated with each other, repeated measurement effects were also incorporated to the statistical model.

The PROC MIXED procedure of SAS (version 8) was used for analyzing the mixed-effects model (Littell et al., 1999). This procedure permits the inclusion of an unequal number of samples (i.e., 20-m reaches) and streams (e.g., OG). For analysis of step geometry, both mean interval lengths and heights of steps in the 20-m reaches were examined for treatment effects. Number of LWD and FWD steps (i.e. classified by primary forming element) and number of LWD and FWD pieces per step in the 20-m reaches were examined. Stream gradient and mean bankfull width were used as covariate terms in the statistical models. If interaction terms such as treatment × stream gradient or treatment × bankfull width were significant in the mixed-effect analysis of covariance (ANCOVA), correlation between the dependent variables and stream gradient and bankfull width were assessed. If interaction terms were not significant, the mixed-effect ANCOVA, including treatment and two covariate effects, was conducted to assess treatment effects (Neter et al., 1996). Then, if treatment effects were significant, Bonferroni multiple comparisons were conducted to estimate the differences among treatments. Additionally, differences in height of LWD steps among treatments were also analyzed by ANCOVA using channel gradient, bankfull width, the number of LWD and FWD pieces and volume of in-channel LWD per 20-m reach as covariate terms. Two-way analysis of variance (ANOVA) was used to determine the effects of channel reach types, treatments, and channel reach type × treatment interaction on interval length and height of steps, number of woody debris pieces, and number of steps formed by woody debris. A significance level of $\alpha = 0.05$ was used for all statistical analyses. All variables in this study were log-transformed to meet the assumptions of normality and variance equality.

A truly randomized statistical design in this observational study is difficult to employ because of the limited numbers of certain stream types in the area. The required size and largely perennial nature of the headwater systems as well as the need to ensure continuity of processes within each system limited our choices of streams in the landscape. Because of difficulties in selecting appropriate variables, observational data does not always provide adequate information on cause and effect relationships in statistical analyses (Neter et al., 1996). However, because the importance of variables in our statistical models was previously demonstrated in the other studies, we rely on the robustness of statistical procedure and inferences of the analysis. To further support our approach and inferences, we note that the landscape from which the streams were selected has basically uniform lithology, soils, climate, hydrological processes, vegetation, and geomorphic processes (i.e., glaciation and deposition of till). Aside from the obvious external management and geomorphic perturbations that dictated the conditions in the LS, YA, YC, CC, and OG channels, the original landscape and climate was approximately uniform; this should minimize any confounding effect of the landscape (i.e., selection bias).

3.4. Results and discussion

3.4.1. Characteristics of woody debris and channel steps

The amount and distribution of woody debris and sediment significantly differed among treatments (Gomi et al., 2001). For instance, numbers of in-channel LWD in the YC and CC channels were significantly larger than those in LS, YA, and OG channels (Table 3.1). Recruitment of logging slash during and after timber harvesting increased the amount of woody debris in the CC and YC streams, although Bilby and Ward (1990) found that the amount of woody debris decreased in managed forest streams in Washington. Free felling of timber without riparian buffer zones may increase the recruitment of logging slash (Swanson et al., 1984). Numbers of FWD in the scour and run out zones of landslides and debris flows in LS and YA channels were significantly lower compared to other streams because landslides and debris flows transported woody debris (Table 3.1).

Relatively higher amounts of sediment were deposited in LS and YA channels compared to CC, YC and OG channels (Gomi et al., 2001). In the YA and CC channels, only numbers of FWD were significantly correlated to sediment volume stored behind woody debris, while both numbers of LWD and FWD were significantly correlated to volume of sediment in OG channels. In YC channels, the number of LWD significantly altered the volume of sediment, while both numbers and volumes of LWD modified the volume of sediment stored behind woody debris (Gomi et al., 2001).

The differences in amount of woody debris and sediment may modify the numbers and types of channel steps. In each treatment, mean height of channel steps ranged from 0.24 to 0.65 m and mean interval length ranged from 2.81 to 9.22 m (Table 3.3). Mean step interval lengths ranged from 1.8 to 7.7 times bankfull width. The mean number of steps per 100 m was highest in CC channels (28.3 to 53.5) and lowest in upper LS channels (9.5 to 21.3). Although Bilby and Ward (1991) noted that diameters of LWD that formed steps in old growth channels were significantly greater compared to those in second growth and clear-cut channels, we did not identify such differences in steps among YC (0.29 m), CC (0.27 m), and OG (0.26 m). Because the diameter of our old-growth riparian stands was small compared to many other old-growth sites in SE Alaska, LWD pieces in OG channels had relatively small diameters and volumes (Gomi et al., 2001).

Formation materials of channel steps may also relate to differences in the amounts and types of woody debris among treatments. Single elements (LWD, FWD, FOD, or boulders) formed 45% of all steps, while 55% of the steps were formed by two or more elements. The percentage of steps formed by LWD was similar among the CC, YC and OG channels (Table 3.3), whereas Bilby and Ward (1991) observed that the percentage of steps formed by LWD in old-growth channels in Washington was significantly higher than in second-growth and clear-cut channels. Because large amounts of logging slash were recruited during and after timber harvesting, CC channels had more steps formed by FWD. LWD and FWD in the upper LS and YA channels formed only 23 and 39% of the steps compared to 55% in lower LS and 53% in lower YA channels (Table 3.3) due to the evacuation of woody debris pieces and boulders from upper reaches during landslides and debris flows. A larger percentage (54%) of the steps formed of LWD were oriented perpendicular to or at an angle ≥ 45° (relative to channels); the remaining 46% of steps formed by LWD were oriented at an angle < 45° relative to the channels. Because channels are narrow, a range of LWD orientations can effectively store sediment and form channel steps.

Treatment effects were significant for several characteristics of step structure, including step interval, number of LWD and FWD steps, and number of FWD pieces per step. However, the interpretation of these treatment effects is complicated by the fact that treatment × channel gradient interaction terms were also significant for all these variables, even though none of them were significantly associated with channel gradient alone (Table 3.4). The relationships between step interval length and channel gradient among treatments is discussed in the next section. In contrast to step interval, step height did not significantly vary among treatments, but did vary with channel gradient ($p < 0.001$) and bankfull width ($p < 0.001$). Height and interval length of steps were weakly correlated in our study ($r = 0.20$, $p = 0.004$) compared to strong correlations found by Chatrand and Whiting (2000). The number of LWD pieces per step also did not vary significantly among treatments ($p = 0.12$), but did vary with bankfull width ($p = 0.026$, Table 3.4).

3.4.2. Length of step interval

Correlations between interval lengths of all steps and channel gradients may differ among treatments because treatment × channel gradient interactions ($F = 4.06$, $p = 0.001$) were significant (Table 3.4). Correlations between step interval length and channel gradient were only significant in OG ($r = -0.63$, $p = 0.001$), lower LS ($r = -0.61$, $p < 0.001$), and upper LS ($r = 0.39$, $p = 0.038$). Similar to findings in OG and lower LS channels, negative correlations between length of step intervals and channel gradients were also observed in Oregon coastal streams (Heede, 1972). Whittaker (1987) estimated an exponential relationship between channel gradient (S: m/m) and length of step intervals (L: m) in mountain streams:

$$L = 0.31\ S^{-1.19}\ (R^2 = 0.68) \quad [2]$$

In both LS and OG channels, we also found a negative exponential relationship in channels with a gradient < 0.25 (Figure 3.3):

$$\text{OG channel (gradient} < 0.25\text{): } L = 0.80\ S^{-0.89}\ (R^2 = 0.58,\ p = 0.006) \quad [3]$$

$$\text{LS channel (gradient} < 0.25\text{): } L = 1.90\ S^{-0.63}\ (R^2 = 0.49,\ p < 0.001) \quad [4]$$

Data from upper and lower reaches of LS channels were pooled for this analysis. Step height did not contribute significantly to these relationships based on stepwise variable selection. Smaller exponents in Eqs. 3 and 4 than in Eq. 2 may relate to different substrate sizes, availability of large roughness elements, flow regimes, downstream fining processes, and geology among the systems (Heede, 1972; Chin, 1999). Although multiple correlation coefficients (R^2) and equation exponents differed from those reported by Whittaker (1987), the three equations did not differ statistically based on 95 % confidence intervals estimated for our data.

Contrary to our findings, previous studies showed weaker correlations between step interval length and channel gradient as well as different coefficients and exponents (Chin, 1999; Chartrand and Whiting, 2000; Duckson and Duckson, 2001). Abrahams et al. (1995) did not find significant correlations between channel gradient and step-interval length. The differences between our findings and the previous studies may relate to different definitions of channel steps (e.g., falls, steps, gravel bars) (Chin, 1989). Moreover, because previous studies mainly focused on step-pool streams, the ranges of gradients were typically much smaller (0.03 to 0.15; e.g., Chin, 1999; Chartrand and Whiting, 2000) compared to our headwater channels. No regular spacing of steps and pools was observed in a headwater stream (gradient < 0.18) in the Okanagan Valley, British Columbia (Zimmermann and Church, 2001). Wohl and Grodeck (1994) found that Eq. 2 best approximated the relationship between channel gradient and step interval length over a wide range of channel gradients.

The relations between the lengths of step intervals and channel gradients were only significant for undisturbed (i.e. OG channels) and extremely disturbed (i.e. LS channels) streams with < 0.25 gradient (Figure 3.3). Even though the woody debris was randomly recruited into the channels, fluvial processes may gradually arrange step intervals with respect to channel gradient in undisturbed (OG) channels. In contrast, catastrophic landslides and debris flows can rearrange the interval length of steps in deposition zones of LS channels. For instance, channel aggradation due to sediment deposition behind log jams may destroy or rearrange channel steps as well as alter channel flow direction. We found that gradient is an important variable that modifies step interval length in LS and OG channels with < 0.25 gradient. However, smaller substrate size and increasing discharge typically accompany decreasing gradient along channels. Control processes of step-interval length may also be associated with substrate size and stream discharge.

Two possible explanations that we could not found the relationships between step interval lengths and channel gradient in CC, YC and YA channels were; ranges of gradient in studied channels and effects of additional woody debris recruitment. Because ranges of channel gradient in studied reaches in CC tended to be smaller and steeper than those in LS and OG, colluvial processes may govern most of the study reaches in CC channels (Table 3.1). LWD and FWD recruited from logging slash and regenerating riparian stands may contribute to formation of steps. Because channel width ranged from 0.8 to 1.9 m, logging slash has not been transported and appears to form steps more randomly in headwater channels. Regeneration of alder in riparian zones of YA and subsequent recruitment of woody debris may also affect more random distribution of steps. Thus, clear exponential relations between the length of step intervals and channel gradients were not detected in CC, YC, and YA streams that had disturbances intermediate in nature between OG (undisturbed) and LS (recent landslide and debris flow disturbances).

Channels with gradient ≥ 0.25 in our OG and LS systems had no clear relations between step interval length and channel gradient. Step-interval lengths in steep OG channels were more constant. Wohl and Grodeck (1994) also found that step interval length was constant in steep channels (> 0.20) of desert streams. Distribution of step intervals in LS channels (≥ 0.25) was more random because of extensive bedrock control (Figure 3.3). Although the energy gradient is higher in steeper channels (≥

0.25), unit discharge in such channels is not sufficient to rearrange the relationships between step interval length and channel gradient. Thus colluvial processes appear to govern the formation of steps through delivery of immobile roughness elements. Wood and sediment are recruited by gravitational processes and are not redistributed through the systems except in channels impacted by mass movement. While the relationship between channel gradient and step interval length in channels < 0.25 steep may be due to hydraulic constraints (fluvial processes), steps in steeper channels (≥ 0.25) were controlled by gravitational (colluvial processes) and geological factors (bedrock control).

3.4.3. Height of steps

Step height may relate to various attributes such as diameter of step forming boulders (Chartrand and Whiting, 2000), diameter of LWD (Wohl et al., 1997), and channel gradient (Chin, 1999). Cumulative ($F = 4.23$, $p = 0.012$) and mean ($F = 5.79$, $p < 0.001$) height significantly differed among treatments for LWD steps. Mean and cumulative step heights in lower LS and YA channels were significantly smaller compared to those in CC channels. Because step heights for all step types combined were significantly correlated to channel gradient (Table 3.4), the differences in step height between both lower LS/YA and CC channels may relate to channel gradient rather than treatment effects. Since the height of channel steps may be related to channel gradient (Wohl and Grodek, 1994; Chin, 1999), gentler gradients in lower LS and YA channels had smaller means and cumulative heights of channel steps than steeper CC channels. Volumes and numbers of in-channel LWD as well as numbers of FWD were significant covariate terms in the model that explained mean heights of LWD steps. Even though Wohl et al. (1997) found relations between step heights and log diameters, diameters of LWD pieces did not correlate to the heights of steps in our study. Similarly, boulder size was significantly correlated to step height in step-pool channels (Wohl et al., 1997; Chartrand and Whiting, 2000). Because our study streams included several types of channel reaches (e.g., step-pool and cascades), substrate, channel morphology, and flow conditions were likely more variable. Thus, clear relationships between step height and wood and boulder size were not found.

3.4.4. Channel steps and reach morphology

Geomorphic processes that dominate at the reach scale are classified as fluvial or colluvial, based on relationships between step interval length and channel gradient in our streams (Figure 3.3) as well as relationships between drainage area and reach gradient in Finney Creek watershed, Washington (see Figure 5 in Montgomery and Buffington, 1997). Montgomery and Buffington (1997) noted that fluvial reaches occurred where channel gradients were < 0.2 to 0.3; such patterns also occurred in other streams in Oregon and Washington. Our study noted a significant relationship between step interval length and channel gradient for gradients < 0.25 (Figure 3.3). A gradient of 0.25 appeared suitable for separating colluvial and fluvial dominated reaches in our study streams. Thus, reach types were evaluated separately for colluvial (gradient ≥ 0.25) and fluvial (< 0.25) portions of channels.

Differences in colluvial and fluvial domination may imply differences in the formation of channel steps: this alters the distribution and types of reaches. Fluvial processes dominated in pool-riffle and step-pool reaches (Table 3.5). Pool-riffle reaches only occurred in lower reaches of LS channels. Colluvial processes only dominated in bedrock reaches of our streams, although Montgomery and Buffington (1997) found bedrock reaches in both colluvial and fluvial reaches. Bedrock, rapids, colluvial cascades and step-step reaches had greater ranges of channel gradient compared to other reach types (Table 3.5). Cascades, step-step, and rapid reaches had both fluvial and colluvial forms. Therefore, both colluvial and fluvial processes may govern formation of cascades, step-step, and rapid reaches. Step-step reaches appear to be transitional between cascades and step-pools with respect to gradient and field observation (Table 3.5).

Channel steps formed by boulders and logs were the major channel roughness features in step-pool, step-step, and cascade reaches. No steps were found in pool-riffle reaches, while few steps were observed in rapids (Table 3.5). Because of the absence of colluvial and fluvial materials, exposed bedrock formed steps in bedrock reaches. Although material can temporarily be stored on exposed bedrock steps, such steps may be unstable due to greater slope gradient and basal shear stress with the exception of steps formed by woody debris pieces (Montgomery et al., 1996). Step intervals among reach types varied significantly ($F = 6.6$, $p < 0.001$); interval length of steps in step-pools and step-steps were longer than in cascade reaches. However, no statistical differences in step interval lengths were found between step-step and step-pools. Mean step intervals in step-pool and fluvial step-step channels were 3.3 and 3.5 times bankfull width, respectively. In contrast, mean step intervals in fluvial cascade channels were only 1.4 times bankfull width. Because channel steps were observed in both colluvial and fluvial dominated reaches, both colluvial and fluvial processes likely contribute to the formation of steps.

Step heights of step-step and cascade reaches were significantly greater than in rapids ($F = 9.3$, $p < 0.003$). Numbers of in-channel LWD and FWD did not statistically differ among reaches, although the lowest numbers of LWD and FWD were found in bedrock channels. The highest percentages of number of steps formed by LWD were in colluvial (59%) and fluvial (54%) reaches of cascades (Table 3.5).

Height (H) and interval length (L) of steps and channel gradient (S) have was examined for the characteristics step-pool reaches. Well-defined step-pool reaches were observed when $(H/L)/S$ ranged from 1.0 to 2.0 based on field and laboratory experiments (Abrahams et al., 1995). Chin (1999), Chartland and Whiting (2000), and Wohl (2000) noted that distinguishable steps-pool reaches were developed with $(H/L)/S > 1.0$. Lenzi (2001) found that $(H/L)/S$ decreased from 1.30 to 0.79 after a large flood event with a recurrence interval of 30-50 yr and noted that this change was associated with a disorganized pattern of step-pool morphology due to deformation of step structures. Mean $(H/L)/S$ per 20 m in step-pool reaches of our streams was only 0.72 (ranging from 0.22 to 2.61); pools and steps in these step-pool reaches appear to be poorly developed. Thus, a larger $(H/L)/S$ ratio is associated with organized patterns of steps and deeper pools and may imply more competent flow. Well-developed step-pool channels are typically formed in sediment-limited conditions (Grant et al., 1990; Montgomery and Buffington, 1997; Chin, 1999). Thus, the smaller $(H/L)/S$ values in our study may reflect more flow-limited conditions and higher supplies of sediment needed to fill the pools.

3.4.5. Distribution of channel reach types

Timber harvesting and mass movement may alter the distribution of reach types in headwater streams. Although differences in reach types were not significant among treatments based on 2-way ANOVA, percentages of dominant channel reach types differed among treatments and between gentler (fluvial) and steeper (colluvial) channel gradients (Figure 3.4). Pool-riffle reaches were only found in the lower sections of LS streams (< 0.25). In upper LS and YA channels (≥ 0.25), 74 and 52% of the reaches were classified as bedrock, respectively. The more extensive bedrock reaches in LS channels likely relate the shorter time period since last mass movement and for the recruitment of woody debris and sediment compared to YA channels. In steeper reaches of OG, CC, and YC channels, 54 to 77% of reaches were classified as step-steps. Step-pool reaches dominated in OG channels with gradients < 0.25, but no step-pool reaches were observed in similar CC channels, which consisted entirely of step-step reaches (Figure 3.4). Despite the different percentages of reach types among treatments, each treatment had a different range of channel gradients; thus, this result is conservative.

In each treatment, downstream changes in reach types were observed as noted by Montgomery and Buffington (1997). Because the amount and distribution of woody debris varied, downstream progression of channel reach types may also differ among treatments. In old-growth channels, cascade, step-step, step-pool, and pool-riffle reaches were sequentially distributed from upper to lower headwater channels (Figure 3.5A). Rapids occurred between the other reach types possibly reflecting local control of channel gradient, discharge, sediment supply, and bedrock lithology. Due to scour and run-out during landslides and debris flows in the LS and YA channels, bedrock and cascade reaches were located in the uppermost parts of headwaters (Figure 3.5B). Subsequently, step-step, step-pool, and pool-riffle reaches were observed in the middle and lower portions of headwaters depending on the location of the sediment deposition zone. Because recruitment of woody debris due to riparian regeneration increased the volume of in-channel LWD in upper YA (3.8 m^3/100m) compared to recruitment in upper LS channels (0.5 m^3/100m) (Gomi et al., 2001), the percentage of step-step reaches increased in steep (≥ 0.25) YA channels compared to LS (Figure 3.5). Such changes in recruitment of woody debris may induce alter bedrock reaches to step-step and other reach types (Montgomery et al., 1996).

Although a limited range of channel gradient was encountered in CC channels, we inferred that low gradient CC channels may shift from step-pool to step-step channels. Because logging debris in headwater streams is typically immobile except during landslides and debris flows (Millard, 2000), it may create steps and buttress significant amounts of sediment. In addition, increases in sediment supply may lead to a shift from step-step to step-pool channels, because the excess supply of sediment may fill pools. Although the effects of logging road that crossed CC 1 and CC 2 channels on amount of woody debris and sediment was not statistically detectable (Gomi et al., 2001), surface erosion from the road surface and ditch may produce sediment. We also observed small bank failures and evidence of soil creep along CC channels. Small to moderate changes in geomorphic and hydrologic processes can alter channel reach types (Montgomery and Buffington, 1997). Thus, in logged streams (CC and YC), step-step reaches were found in long spans of headwater channels at lower channel gradients (Figure 3.5C). Distribution of channel reach types is strongly affected by the amount of woody debris loading, sediment supply, transport, and sorting processes related to flow generation in headwater streams (Montgomery and Buffington, 1997; Rot et al., 2000).

3.4.6. Effects of timber harvesting and mass movement

Channel unit scale

Differences in the amount of LWD and FWD and in-stream function of woody debris for storing sediment appeared to alter the formation of channel steps among treatments. Numbers of steps and total height of steps in the CC channels may increase due to greater woody debris recruitment

(Table 3.1 and 3.2). Because different types of woody debris (LWD and FWD) determine the volume of sediment storage among treatments (Gomi et al., 2001), different types of woody and organic debris may contribute differently to formation of channel steps. These differences are important in relation to the stability of channel steps. Large woody debris steps may be stable for 50 to 200 years (Harmon et al., 1986) unless the entire headwater system is impacted by landslides and debris flows; however FWD and FOD steps are much more unstable (e.g., Millard, 2000).

Changes in number and structure of steps formed by woody debris are associated with long-term recruitment of wood from riparian stands. Likens and Bilby (1982) noted that regeneration of deciduous alder and subsequent coniferous stands in riparian zones after logging altered the number of woody debris dams in channels. In our study, mean diameter at breast height (DBH) of trees in riparian zones was larger than the mean diameter of LWD steps in OG systems (Figure 3.6), although the diameters of LWD pieces did not strictly represent DBH of LWD pieces. In contrast, mean DBH of riparian stands was smaller than diameters of LWD in steps of LS, YA, and YC channels (Figure 3.6), even though the YA and YC riparian stands regenerated for 30 to 40 yr after timber harvesting and mass movement. Steps formed by LWD with diameters larger than riparian DBH represent legacies from previous old-growth stands. Smaller woody debris and deciduous wood (alder) decompose and fragment rapidly (Harmon et al., 1986). This breakdown alters the stability of steps as well as sediment storage. Potential woody debris from old-growth riparian zones will remain larger diameter and may reside in channels for longer periods comparted to the other treatremsnts, because of the large DBH of riparian stands.

The effect of woody debris on channel geomorphology largely depends on biogeoclimatic factors. For instance, woody debris had little influence on channel morphology in streams of Sierra Nevada, CA, USA (bankfull width ranged from 2.1 to 7.5 m), because the size of woody debris were small relative to channel dimensions (Berg et al., 1998). Channel steps in such systems are more likely controlled by boulders and cobbles instead of woody debris. Thus, the effects of timber harvesting and disturbance in such streams may be different than in our streams.

Channel reach scales

In hierarchical stream ecosystems, changes in the larger-scale system will affect the structure of smaller-scale systems (Frissell et al., 1986). Management and disturbance regimes in headwater streams also alter channel morphology at different hierarchical levels of stream ecosystems (Figure 3.7). Longitudinal profiles of headwater segments in SE Alaska are typically concave with steep upper reaches and gentle lower reaches because of glaciation. Sediment deposition from landslides and debris flows typically occurs before headwater channels enter major rivers due to the lower channel gradient in the bottom of U-shaped valleys (Gomi et al., 2001). The locations of scour, runout, and deposition during and immediately following mass movement alter channel reach types (Montgomery and Buffington, 1997). For instance, bedrock reaches were typically located in scour and runout zones of landslides and debris flows. Cascade, step-step, and step-pool reaches were rearranged in the deposition zone of debris flows. Such rearrangement of channel reach types also modifies distribution and structure of channel steps (Figure 3.7).

Changes in the recruitment of woody debris affect the number of channel steps and reach types. Because in-channel woody debris alters substrate size and channel morphology (Woodsmith and Buffington, 1996), decreasing the woody debris loading can increase pool spacing and shift step-pool and step-step reaches to plane-bed and bedrock reaches (Montgomery and Buffington, 1998). In contrast, step-pool channels possibly shift to step-step and cascade reaches if channel roughness increases, thus storing more sediment and impeding the creation of pools due to recruitment of logging slash. However, for longer periods, such logging slash decays and has little influential on the formation of steps. Woody debris recruitment from regenerating riparian alder stands promotes the shift from bedrock to cascade and step-step reaches.

In conjunction to changes in amount of woody debris, changes in sediment supply modify the distribution and types of steps and channel reaches. Because of supply-limited condition for sediment, bedrock channels did not convert to forced pool-riffle channels despite loading of LWD in streams of the Cascade Range in Washington (Rot et al., 2000). Thus, the presence of woody debris, due to timber harvesting and riparian stand regeneration, is one element that influences headwater channels; time, sediment supply and size of streams are also important for understanding cause and response to timber harvesting and mass movement. Consequently, changes in the recruitment of woody debris and sediment alter the number and types of channel steps, and subsequently modify channel reach types (Figure 3.7). Channel steps can be controlled by chronic woody debris inputs (e.g., riparian regeneration and bank erosion), and transport and accumulation of woody debris during episodic events (e.g., mass movements).

3.5. Summary and conclusion

External influences such as the history of timber harvesting and mass movement modified channel steps and reach morphology in headwater streams. Both woody debris and sediment supply are important for the formation of channel steps and reach types. For undisturbed conditions (OG) with gradients < 0.25, step interval length and channel gradient followed an exponential relationship attributed to fluvial processes. Channel steps were arranged with exponential relationship to channel gradient for long term undisturbed conditions. Exponential relationships between channel gradient and step interval length were also significant in stream channels with recent landslides and debris flows with gradients < 0.25 (LS). Location of scour, runout, and deposition of sediment and woody debris from landslides and debris flows modified the distribution of reach types and the structure of steps within reaches. Although ranges in channel gradient were limited, woody debris recruitment from logging in CC and YC channels and from alder stands in YA channels affects channel steps and reach morphology. Because such woody debris is typically immobile in narrow channels (Millard, 2000), woody debris pieces creates channel obstructions such as steps and alter sediment movement. In addition, sediment supply may also contribute to step formation and alter channel morphology. Thus, woody debris recruited by logging and riparian stands modified channel reach types by forming steps.

Processes for the formation of channel steps have been discussed in other studies (Whittaker, 1987; Abrahams et al., 1995; Zimmermann and Church, 2001). Our preliminary results show the amount of woody debris and sediment are important factors in characterizing channel steps and altering reach morphology. Changes in the amount of woody debris and sediment, which relate to mass movement and timber harvest history and their recovery processes, alter the spatial and temporal formation of channel steps and distribution of reach morphology. Such variations are important factors controlling the dynamics of sediment, water, nutrients, and organic matter in headwater channels (Sidle et al., 2000). Recently the role and linkages of headwater systems in the restoration and management of downstream reaches has attracted more attention (Sidle, 2000). Studies of timber harvesting and mass movement effects on various channel morphology in headwater streams will provide information needed for the conservation and management of major stream systems.

Table 3.1 Characteristics of the study sites.

	Drainage area (km^2) [c]	Surveyed channel length (m)	Mean gradient (m/m) [a]	Mean bankfull width (m) [a]	Exposed bedrock (% length)	Number of LWD per 100m		Number of FWD per 100m	Date of landslides and debris flows
						Total	In-channel		
LS1 Upper [b]		225	0.40 (0.11)	1.2 (0.6)	26.7	15	4	15	1993/1979
LS1 Lower	0.21	400	0.10 (0.06)	2.6 (1.5)	0.0	40	29	106	
LS2 Upper [b]		150	0.31 (0.12)	1.6 (0.4)	40.7	37	27	67	1993
LS2 Lower	0.27	250	0.14 (0.06)	1.8 (0.6)	0.0	54	45	71	
LS3 Upper [b]		300	0.32 (0.12)	2.8 (1.3)	59.8	57	27	53	1993
LS3 Lower	0.35	350	0.10 (0.08)	3.7 (1.3)	0.0	80	46	116	
YA1 Upper [b]		120	0.37 (0.09)	1.1 (0.5)	26.0	24	21	41	1961
YA1 Lower	0.22	100	0.18 (0.07)	1.4 (0.5)	2.0	52	37	82	
YA2 Upper [b]		225	0.43 (0.09)	0.9 (0.3)	38.0	20	16	55	1961
YA2 Lower	0.14	125	0.19 (0.07)	0.9 (0.3)	0.0	14	14	48	
YA3 Upper [b]		150	0.29 (0.11)	2.0 (0.6)	47.1	29	23	27	1979/1961
YA3 Lower	0.21	300	0.17 (0.07)	1.9 (0.6)	0.0	66	59	105	
YC1	0.24	300	0.24 (0.06)	1.2 (0.4)	0.0	52	34	130	
YC2	0.12	100	0.43 (0.12)	0.6 (0.4)	0.0	80	35	102	
YC3	0.26	250	0.26 (0.07)	1.9 (1.0)	21.9	116	66	399	
CC1	0.20	400	0.36 (0.12)	0.9 (0.3)	0.1	67	46	144	
CC2	0.20	250	0.37 (0.11)	0.8 (0.2)	0.1	52	32	105	
CC3	0.19	225	0.40 (0.08)	1.3 (0.7)	0.0	82	65	151	
OG1	0.19	150	0.41 (0.12)	0.8 (0.4)	13.4	31	21	124	
OG2	0.22	150	0.45 (0.09)	1.6 (1.1)	26.9	41	24	143	
OG3	0.25	200	0.09 (0.04)	1.9 (0.6)	0.1	52	33	150	
OG4	0.22	200	0.27 (0.03)	1.2 (0.2)	0.1	68	45	103	

Note: LS, recent landslide (landslide and debris flows in 1979 and (or) 1993); YA, young alder riparian forest (logged from 1953 to 1957 and landslide and debris flows in 1961 and (or) 1979; YC, young conifer riparian forest (logged from 1959 to 1961); CC, clear cut (logged in 1995); OG, old-growth sites.

[a] Values are means with standard deviation given in parentheses.

[b] Sites are divided into scour and runout (upper section) and deposition (lower section) zones of landslides/debris flows.

[c] Drainage areas were estimated at the lower end of study streams from USGS topographic map (Crag C-3) using digital planimeter.

Table 3.2 Classification of channel reach types

	Pool-riffle	Step-pool	Step-step	Rapids	Cascade	Bedrock
Typical bed material	Gravel-cobble	Cobble-Boulder	Cobble-boulder	Gravel, Cobble, Boulder	Boulder	Rock
Bedform patterns	Laterally oscillatory	Vertically oscillatory	Vertically oscillatory	Featureless	Random	Irregular
Dominant roughness element	Bars, pools, grains sinuosity, banks	Steps, pools, grains, banks	Steps, grains, banks	Grains, banks	Grains, banks	Channel beds, banks
Dominant sediment storage	Overbank	Bed form (top and bottom of steps)	Bed form (top and bottom of steps)	On bed, side of flow obstructions	On bed, side of flow obstructions	Bedrock pocket
Typical confinement	Unconfined	Confined	Confined	Confined	Confined	Confined
Typical pool spacing (Channel widths)	1 to 5	1 to 4	None	None	< 1	Variable
Sources of Definition	Montgomery et al. (1995) Montgomery and Buffington (1997)	Whittaker (1987) Montgomery and Buffington (1997)		Zimmerman and Church (2001)	Montgomery and Buffington (1997)	Montgomery and Buffington (1997) Wohl (2000)

Note: Some diagnostic features were modified from original sources of reach type definition to adapt to study streams of southeast Alaska.

Table 3.3 Characteristics of channel steps.

	Number of Steps per 100m	Mean height of step (m)	Mean interval of steps (m)	Percentage				Mean number of LWD per step primary formed by LWD
				LWD steps	FWD/ FOD steps	Boulder steps	Bedrock steps	
LS1 Upper	9.5	0.4	5.6	0	0	36	64	0
LS1 Lower	12.5	0.3	7.8	52	18	26	0	1.4
LS2 Upper	21.3	0.5	4.8	19	0	56	22	1.3
LS2 Lower	12.4	0.4	8.5	46	12	42	0	3.5
LS3 Upper	13.0	0.5	6.6	29	13	37	21	1.6
LS3 Lower	10.6	0.5	10.7	38	5	54	0	3.5
YA1 Upper	16.7	0.6	5.7	17	28	39	17	1.0
YA1 Lower	17.0	0.5	5.9	59	12	18	12	2.0
YA2 Upper	13.8	0.4	4.8	23	41	36	0	1.1
YA2 Lower	18.4	0.2	4.8	30	20	40	10	1.2
YA3 Upper	20.0	0.4	4.8	23	23	30	23	1.6
YA3 Lower	19.3	0.4	3.4	45	7	47	0	2.4
YC1	14.7	0.5	6.2	42	9	44	0	1.2
YC2	11.0	0.5	5.0	18	18	64	0	1.0
YC3	21.6	0.5	4.7	33	31	24	11	1.6
CC1	53.5	0.4	3.5	36	30	34	0	1.9
CC2	45.8	0.5	3.8	39	33	25	0	1.6
CC3	28.4	0.5	3.9	34	36	35	0	1.5
OG1	21.3	0.4	4.4	22	16	44	19	1.4
OG2	24.0	0.4	4.1	24	28	28	20	1.3
OG3	12.0	0.3	7.8	46	25	25	4	2.1
OG4	34.5	0.4	2.9	41	10	44	1	1.6

Note: see Table 1 for description of treatments.

Table 3.4 Summary of mixed effect ANCOVA for the geometry and structures of steps.

		Treatment (T)	Stream gradient (S)	Bankfull width	T×S
Step interval	F	4.40	0.01	Not significant	4.06
	P-value	***< 0.01***	0.94		***<0.01***
Step height	F	0.35	28.70	15.28	Not significant
	P-value	0.90	***<0.01***	***<0.01***	
Number of LWD steps	F	6.20	0.01	Not significant	6.56
	P-value	***<0.01***	0.99		***<0.01***
Number of FWD steps	F	3.17	1.69	Not significant	3.17
	P-value	***< 0.01***	0.20		***<0.01***
Number of LWD pieces per steps	F	1.75	Not significant	5.13	Not significant
	P-value	0.12		***0.03***	
Number of FWD pieces per steps	F	2.51	0.92	Not significant	3.10
	P-value	***0.03***	0.34		***0.01***

Note: Significant p-values are listed in bold italics.

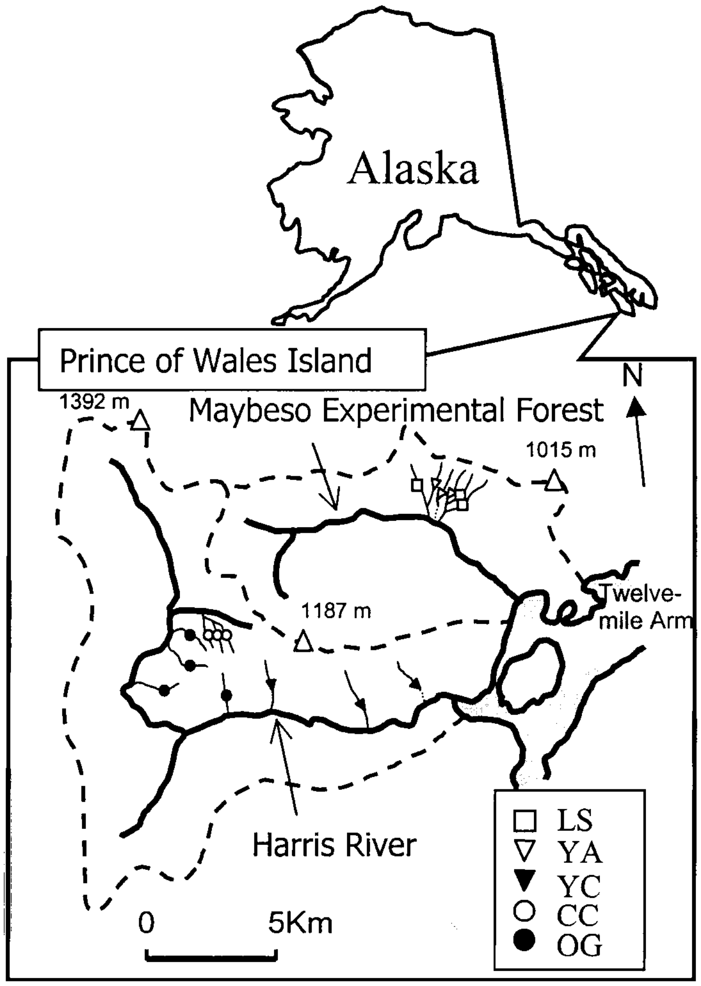


Figure 3.1 Location of study sites in headwater streams of Maybeso Experimental Forest and the Harris river basin. Broken line shows watershed boundary. See Table 1 for definition of the treatment codes.

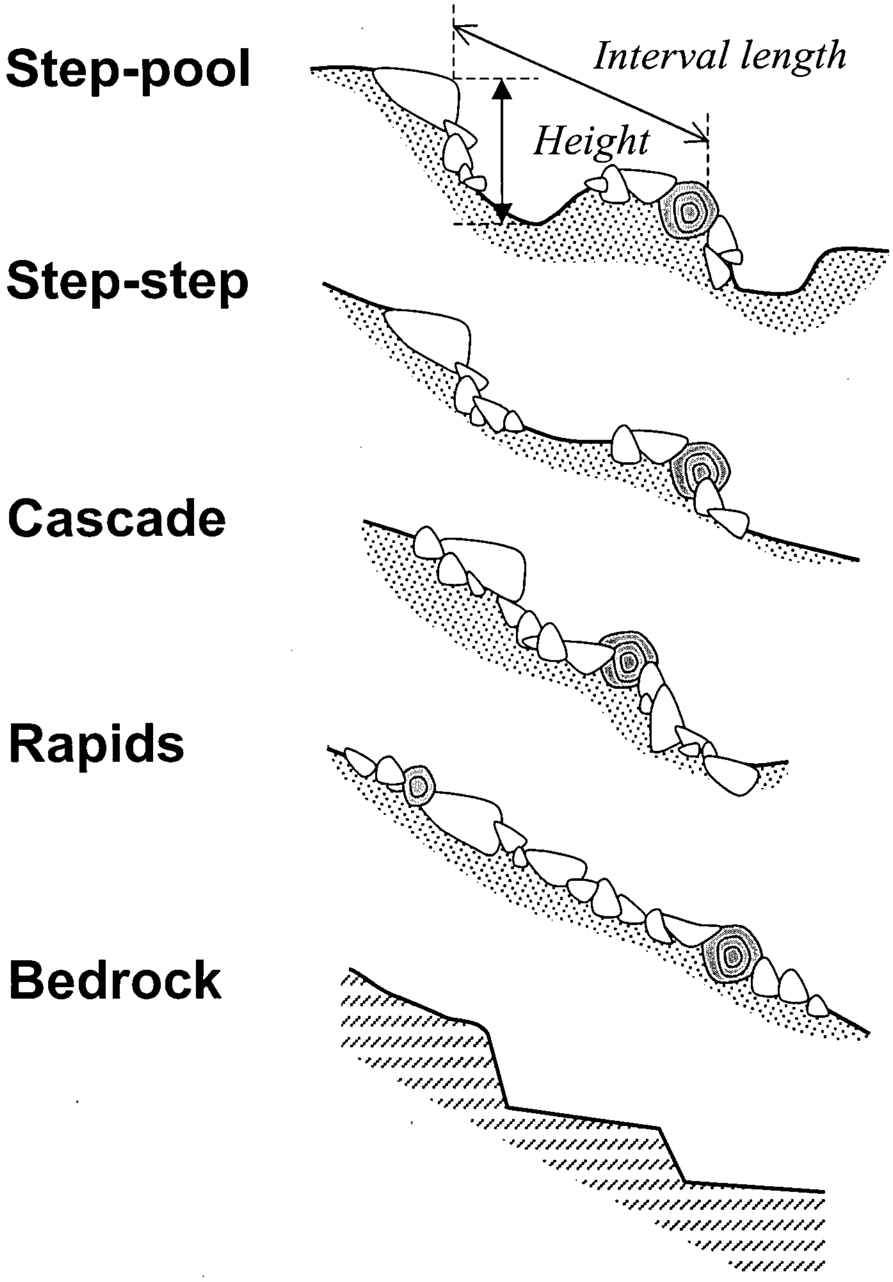


Figure 3.2 Schematic profiles of channel reach types.

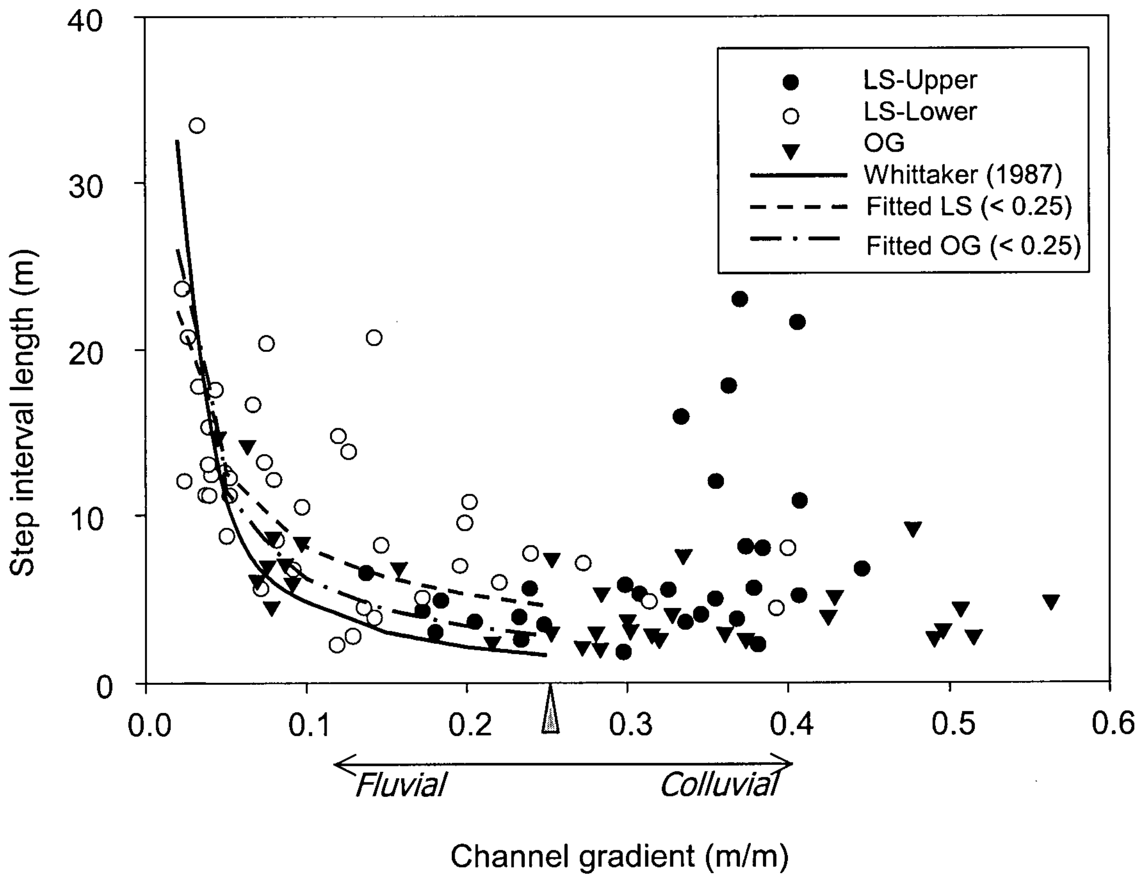


Figure 3.3 Mean length of step intervals in relation to channel gradient for 20m reaches in OG and LS channels. Channels with gradient lower than 0.25 were dominated by fluvial processes, and have significant exponential relations between step interval length and channel gradient.

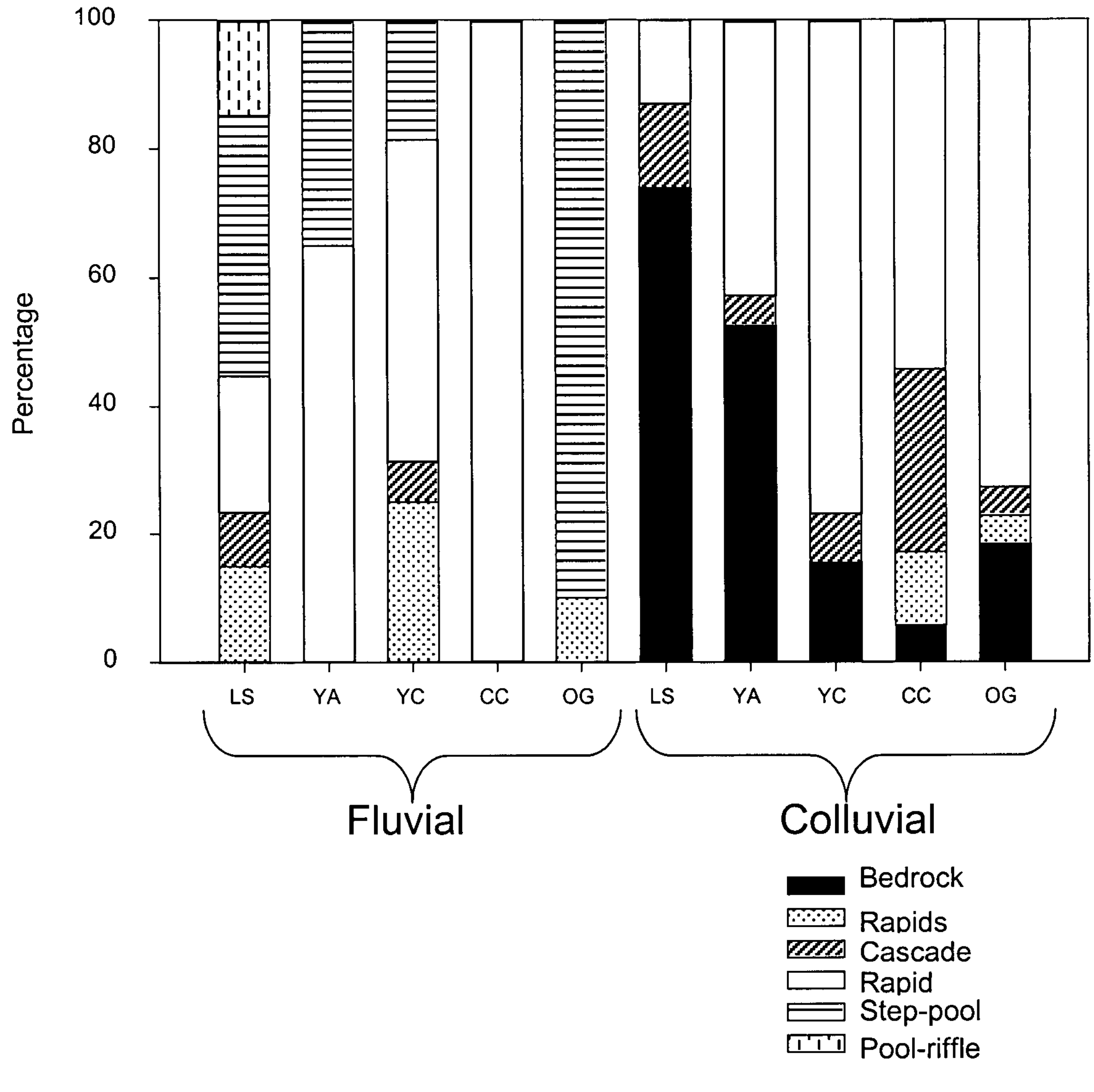


Figure 3.4 Percentages of channel reach types among treatments as well as between fluvial and colluvial domination.

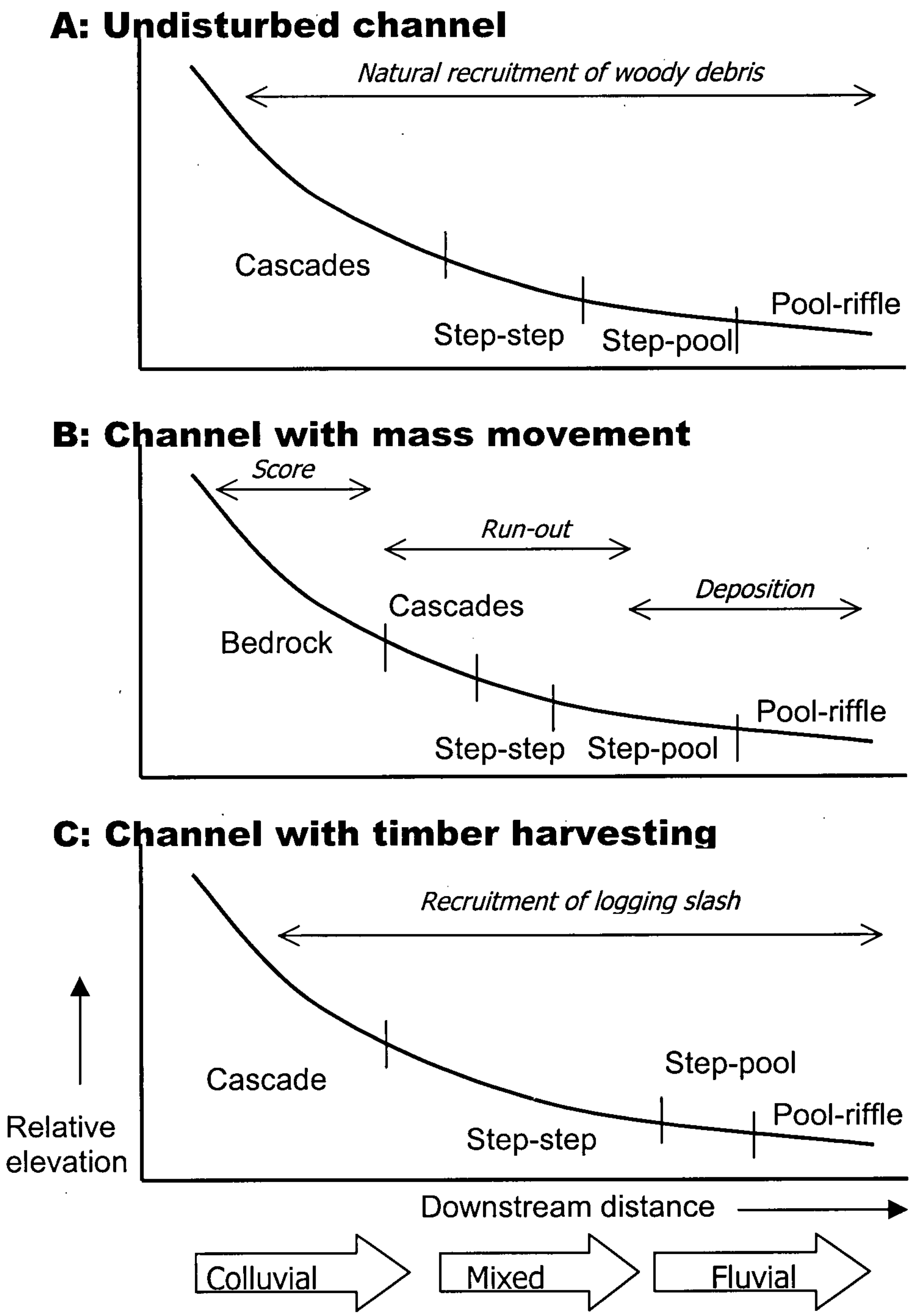


Figure 3.5 Schematic longitudinal profile showing the distribution of channel reaches in three types of headwater streams: A) an undisturbed channel; B) a landslides/debris flow channel; and C) a logged channel.

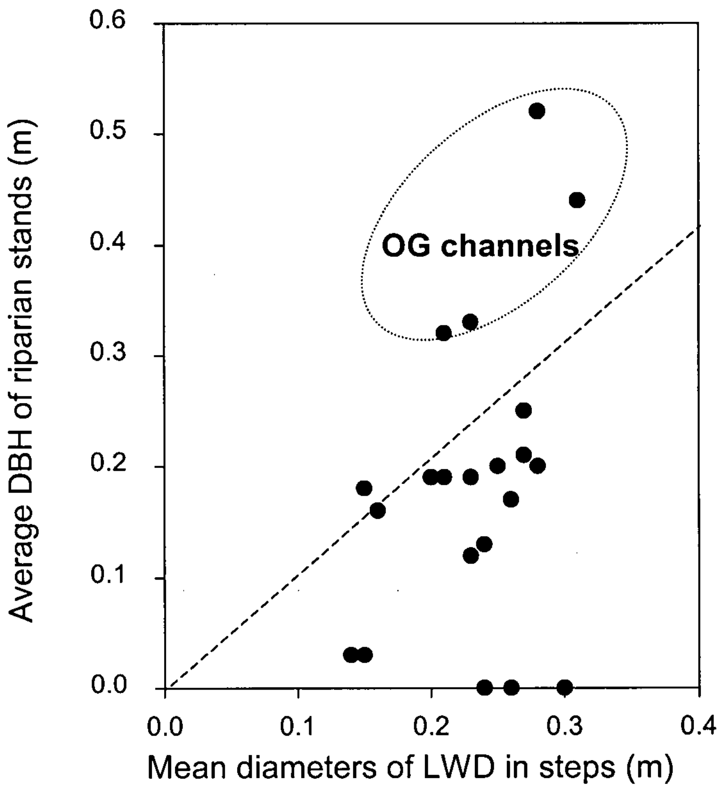


Figure 3.6 Relationships between riparian stands DBH and step LWD diameters. Dashed line shows equal diameter of LWD in steps and average DBH of riparian stands.

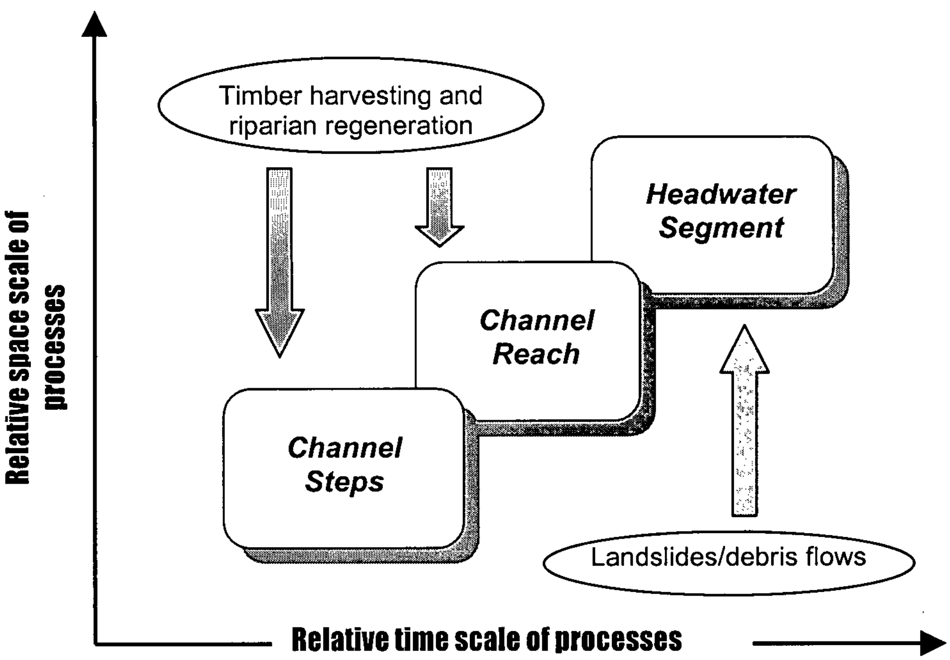


Figure 3.7 Effect of management and disturbance regimes on geomorphic attributes in headwater streams. Landslides and debris flows modify channel reach types and then alter channel steps. In contrast, timber harvesting alters channel steps and then modifies channel reach types.

Chapter 4

Bedload and suspended sediment transport

4.1. Introduction

Headwater streams are the primary sources of sediment within most channel networks. Because the total area of headwater systems comprises the major portion of a watershed, sediment from headwaters contributes significantly to material dynamics in downstream systems [Schumm, 1956]. Both bedload and suspended sediment produced from headwaters affect channel morphology in downstream systems [Lisle, 1987]. Changes in sediment supply modify habitat for fish and macroinvertebrates as well as the distribution of spawning gravel and survival of salmonid eggs [Lisle and Hilton, 1992; Beechie, 2001].

The sediment dynamics of steep headwater channels (> 0.05 in channel gradient) may differ from those of low gradient channels. In particular, boundary conditions controlling bedload and suspended sediment entrainment appear to be more complex in headwater streams. For instance, sizes of sediment in headwaters vary widely compared to those in lower gradient channels [Lisle, 1995]. Interlocking structures of cobbles and boulders create channel steps and stabilize channel bed [Grant et al., 1990; Church et al., 1998; Zimmerman and Church 2001]. In contrast, high-energy gradients and strongly turbulent flow caused by large substrate may initiate more intense sediment transport [Lisle, 1987]. In forested streams, woody debris from riparian stands affects channel roughness and creates storage sites: this thus modifies the amount and regime of sediment transport [Sidle, 1988; Woodsmith and Buffington, 1995; Buffington and Montgomery, 1999a]. Relatively smaller pieces of woody debris can also contribute to sediment storage in headwater channels [Gomi et al., 2001].

External influences such as mass movement and timber harvesting create spatial and temporal variations in amount of sediment and woody debris in forested headwater streams [Benda and Dunne 1997]. Larger amounts of sediment originate from episodic mass movement such as landslides and debris flows [Sidle et al., 1985]. Mass movement affects the abundance and distribution of sediment and woody debris [Gomi et al., 2001]. Furthermore, 20 to 30 years after disturbances, regenerated riparian stands begin recruiting woody debris pieces. Logging activities in headwater catchments may also alter the amount of bedload and suspended sediment transport in channels due to mass movement and bank failures [e.g., Grant and Wolff, 1991]. Logging slash (small wood and branches) that remains in headwater channels creates sites for sediment storage [Millard, 2000; Gomi et al., 2001]. Because hillslopes, zero-order basins, and stream channels are tightly coupled within headwater systems, changes in linkages between channels and hillslopes (e.g., vegetation coverage) due to mass movement and timber harvesting may directly affect the supply and transport of sediment.

Despite such spatial and temporal variations in headwater systems, the dynamics of bedload and suspended sediment in such steep headwater channels has not been extensively studied through field observations and laboratory experimentation compared to low gradient channels. The application of theoretical sediment transport equations to headwater streams is difficult because of the non-uniform conditions created by greater variations in velocity, channel geometry, roughness, and sediment supply [Lisle, 1987; Adenlof and Wohl, 1994; Rickenmann, 2001; Zimmerman and Church, 2001]. In addition, changes in sediment and woody debris supply related to management and disturbance histories are likely to dictate the types and amounts of sediment movement and the effective discharge for initiating bedload sediment movement [Buffington and Montgomery, 1999b; Hassan and Church, 2001]. Therefore, the objective of this study is to evaluate the amount and sizes of bedload and suspended sediment transport in steep-gradient headwater streams with different mass movement and timber harvesting histories.

4.2. Study sites

Four headwater streams were selected in the Maybeso Experimental Forest and the adjacent Harris River basin within the Tongass National Forest on Prince of Wales Island, southeast Alaska (Figure 4.1). The drainage areas of the Maybeso watershed and Harris River basin are 39.4 and 82.4 km^2, respectively. The climate in this area is humid, cool and temperate. The mean annual temperature is 10°C and the mean annual precipitation is 2800 mm. About 40 % of this precipitation occurs during rainstorms from September through November. As such, most bedload transport and landslide activity occurs during this autumn period [Sidle, 1988]. The basin is characterized by a U-shaped deglaciated valley covered by a veneer of glacial till (of varying thickness) below 1000 m in elevation [Swanston, 1970].

Dominant forest vegetation includes western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*) and red alder (*Alnus rubra*). Species distribution in headwater systems, particularly the occurrence of alder, is highly influenced by past disturbance regimes such as landslides and debris flows. In the late 1950's, 25.4% of the Maybeso watershed and 20.0 % of Harris River basin were clear-cut logged using cable methods. Small cut-block logging was also conducted in the Harris basin in 1995.

Four types of headwater streams reflecting different management and disturbance histories in channels and riparian zones were selected in the Maybeso and Harris watersheds (Figure 4.1; Table 4.1). These four types are: old-growth (OG); recent (3-year old) clear-cut (CC); young-growth (40 years after clear-cutting) alder riparian forest (YA); and recent mass movement channels (LS). These four stream types have different characteristics of accumulation and distribution of woody debris and sediment [Gomi et al., 2001]. The OG stream and the surrounding forest had not been affected by logging activities or recognizable mass movement during the last 100 to 300 years. In the CC channel, the surrounding forest was logged without a riparian buffer zone. Large amounts of logging slash were left in and around the channel, but no visible past or recent mass movement impacted the channel [Gomi et al. 2001]. The YA and LS streams were affected by timber harvesting (from 1957 to 1959) and by mass movement (in 1961 and 1993) (Table 4.1). The most recent landslide activity occurred during an October 1993 rainstorm and affected only the LS channel. Sediment and woody debris produced by landslides was typically transported as channelized debris flows and formed jams in the deposition zones [Figure 2 in Gomi et al. 2001]. Relatively smaller amounts and sizes of woody debris pieces were found in LS (Table 4.1). The amount of woody debris is higher in the YA channel compared to the LS channel because of the recruitment of woody debris from riparian alder stands after 1961 mass movement in YA. The lower ends of the deposition zones did not reach the main channel of Maybeso Creek due to the wide, flat valley bottom. These study streams are representative of steep glaciated forest landscapes in southeast Alaska and are controlled by similar biogeoclimatic factors such as vegetation, precipitation, glaciation, and lithology.

V-notch weirs (120°) were installed in the summer of 1999 to measure discharge and sediment yield in the four streams. In the LS and YA channels, weirs were located between the upper zone (source area and run-out zone of debris flows) and the lower depositional zone for debris flows. Therefore, we monitored sediment transport in upper reaches that were once affected sources and run-out paths of debris flows. Cascade, rapid, and bedrock reaches were dominant upstream of the weirs [Montgomery and Buffington, 1997; Zimmerman and Church, 2001]. Drainage areas at the weirs ranged from 2.1 to 2.5 ha based on field measurements of length and width of contributing areas, including channels, zero-order basins, and hillslopes (Table 4.1). Although the measured drainage areas were considerably smaller than those estimated from GIS maps (ranging from 10 to 15 ha), the areas based on field measurements may be more accurate representations of hydrological contributing area. Mean channel gradients of the headwater channels ranged from 0.27 to 0.40, and mean bankfull widths ranged from 0.9 to 1.2 m (Table 4.1). Due to landslides and debris flows, 26% of the upper reaches of the LS and YA channels was exposed bedrock, although greater amounts of sediment were stored within the LS and YA channels compared to CC and OG (Table 4.1) [Gomi et al., 2001].

4.3. Methodology

Bedload deposition, movement of bedload tracers, suspended sediment concentration, stream discharge, and precipitation were monitored during a storm season, from September to November 1999. In all four streams, discharge levels (based on water stage in the V-notch weirs) were monitored every 10 minutes using a pressure transducer connected to a data logger. Discharge (Q) was estimated by a stage-discharge equation for a 120° weir [Gregory and Walling, 1973]. Precipitation was also monitored in 10-minute intervals using a tipping bucket rain gauge at an open-canopy area near the LS and CC channels. Sediment deposited in weir basins was sampled when significant volumes accumulated, generally after each major storm event. Sampled sediment was sieved into size classes of 11.2, 16.0, 25.0, 32.0, 45.0 and 115.0 mm, and weighed in the field. Organic matter was removed by hand for these larger size classes. Sediment < 11.2 mm was transported to the laboratory, dried, and then weighed for smaller sieve classes (4.75, 2.00, 1.00, and 0.425 mm). Particles ≥ 1 mm were considered as bedload sediment. Although weir basin captured particles < 1mm, such fine particles were often suspended during storm event and thus considered as suspended sediment. Sub-samples of finer bedload sediment (< 11.2 mm) were burned for 2 hours at 500°C to calibrate the organic matter content in each sieve class [Sidle, 1988]. The largest peak discharges that *did not* initiate substantial bedload movement were estimated as the threshold discharge (Q_T) for entraining bedload sediment. Effective discharge (Q_E) for transporting bedload material is calculated as

$$Q_E = Q - Q_T \qquad [1]$$

Where, Q is the actual stream discharge during a storm. The effective discharge volume (V_E) was also calculated from effective discharge.

Behaviors of bedload materials such as mobile distance and trapped location were characterized using bedload tracers. Fifty natural bedload tracers (large gravel particles painted green and orange) were placed upstream of the two monitoring reaches in each stream on September 15, 1999. Average diameters of bedload tracers ranged from 28.4 to 30.2 mm, corresponding to D_{30} to D_{50} of the channel bed substrate (Table 4.1). The dominant factors influencing entrapment of displaced tracers were classified as woody debris steps, log jams, boulder steps, bank sides, and mid-channel zones. The largest peak discharges that *did not* initiate tracer movement were estimated as the threshold discharge for entraining bedload tracers.

To monitor changes in channel morphology, two 25 m reaches (M1 and M2) were located 50 and 100 m upstream of the weirs in three streams (the exception being the YA stream). In the YA stream, one monitoring reach was located 50 m downstream of the weir and another reach was located 100 m upstream of the weir. Movement of woody debris pieces and boulders as well as the accumulation of fine organic debris was monitored on three occasions, generally after major storm events.

Suspended sediment was measured using an automatic pumping sampler during selected storm events. The intake of the pumping sampler was attached to a metal rod and suspended in mid-stream. This minimized the effects of flow separation and clogging by organic matter for sampling efficiency [Sidle and Campbell, 1985]. For most flows, the intake was located a few centimeters above the streambed and at least 1 m upstream of the weir ponds. We assumed that the sampled water was well-mixed and that there was no significant difference in suspended solids with changes in the flow depth. Sampling was automatically activated by stormflow stage. A 500 ml sample was collected every 10 or 15 minutes. Because only 24 sample bottles were contained in the sampler, suspended sediment responses were typically measured only during the rising limbs of major flood events. Samples were transported to the Hollis field station (Figure 4.1) where they were analyzed. Total suspended solids (TSS) were determined by passing a known volume of stream water through a glass fiber filter with an effective retention of 1.2 μm; filters were oven dried at 100 °C and residual sediment was weighed. Suspended sediment (SS), the mineral portion of the sample, was weighed after the TSS sample was burned at 550 °C for approximately 2 hours [Sidle and Campbell, 1985].

The locations and types of probable sediment sources in channels, hillslopes, and zero-order basins upstream of the weirs were described and mapped before monitoring began. New potential sediment sources were identified after major storm events if significant changes in hillslopes, zero-order basins, and channels were observed.

To evaluate the role of woody debris on sediment movement in headwater channels, the distribution and accumulation of woody debris and sediment were measured in 200 m upper reaches [Gomi et al., 2001]. Organic debris in streams was divided into woody debris and fine organic debris

(FOD). Woody debris was further classified into two categories: large woody debris (LWD: pieces ≥ 0.5 m in length and ≥ 0.1 m in diameter) and fine woody debris (FWD: pieces ≥ 0.5 m in length and 0.03 to 0.1 m in diameter). To quantify the distribution and accumulation of woody debris at each site, the following properties of LWD were measured: in-channel, bankfull, and total lengths; diameter; position; and orientation. In-channel length was measured for either the entire piece or portion of the LWD piece located within the wetted channel. Bankfull length was defined as the portion of LWD pieces within the bankfull width. Total length of LWD pieces, including terrestrial portions, was also measured. Volume of large woody debris (V: m^3) was calculated as follows for in-channel, bankfull, and total volume components of LWD:

$$V = \pi \, (D/2)^2 \, L \qquad [2]$$

where, D is the mid-log diameter and L is the appropriate length. Fine organic debris (FOD) was classified based on the level of accumulation [Gomi et al., 2001].

Sediment storage behind woody debris and other obstructions such as boulders and bedrock was measured in these headwater streams. The shape of sediment wedge was approximated as rectangular pyramid, and then volume was calculated from width (w), length (L_w), and average depth (d):

$$\text{Sediment volume} = (w \, L_w \, d)/3 \qquad [3]$$

The average depth of the sediment wedge was measured using a sediment probe at several points. The cause of sediment deposition was categorized according to the formation elements of the debris dam: LWD, FWD, FOD, boulders, or bedrock. At a several locations along the channels, the median of 100 pebbles in a 0.2 × 0.2 m grid was measured to provide an indication the size of mobile streambed material [Wolman, 1954]. Minimum size for measurable substrate was 1 mm. Large cobble and bolder components > 0.2 m were excluded because of their relative immobility except during landslide and debris flow events [Sidle, 1988; Zimmerman and Church, 2001].

4.4. Bedload sediment

4.4.1. Peak flow characteristics and bedload transport

Stormflow attributes such as peak discharge and flow duration characterize the amount of bedload transport in stream channels. We observed nine bedload events (only eight bedload samples were taken in the OG channel) during the autumn 1999 monitoring period (Table 4.2). Rickenmann [1997] found that average 20 bedload transport events occurred per year in an active mountain stream of Switzerland. In contrast, Sidle [1988] observed that bedload entraining discharge occurred at least two to three times during the storm season in a low gradient stream in southeast Alaska. Therefore, relatively frequent bedload transport was observed in our streams. Threshold discharge levels of these bedload events ranged from 3.44×10^{-3} to 5.91×10^{-3} $m^3 s^{-1}$ and were approximately five times larger than the minimum measured discharge (Table 4.1). The largest peak discharge and greatest bedload movement occurred on October 21 in all four streams. Recurrence interval of the largest storm event was $\approx$ 1.5 yr based on 20-yr records of 24-hr precipitation at Hollis.

Total bedload yield throughout the monitoring period varied among streams. Cumulative bedload yield in four streams were approximately liner property with respect to cumulative effective discharge volume (Figure 4.2) [Rickenmann, 2001]. The slope of the cumulative sediment transport versus cumulative volume of effective discharge plot was the steepest for the LS channel. About 1900 kg of bedload sediment was measured in LS during the 1999 storm season, although cumulative effective discharge was the smallest of the four streams (Figure 4.2). This indicates that sediment was constantly supplied throughout the storm season. Particularly, a small slope failure occurred 30 m upstream of the weir during the largest storm event (October 21). The failure delivered about 1.5 to 2.0 m^3 of sediment (largely weathered till [clay and silt] and coarse fragments) to the channel based on dimensional estimates. Cumulative bedload transport plots were much less steep in YA, CC and

OG channels with progressively less bedload sediment being transported with increasing cumulative effective discharge later in the storm season (Figure 4.2).

Peak discharge and effective discharge volumes are important parameters in estimating total bedload yield during storms. Rickenmann [1997] formulated the following relationship for total mass of bedload per unit contributing area that was deposited behind a weir during individual storms (B, kg ha^{-1}) as a function of peak discharge (Q_P, $m^3\ s^{-1}$), threshold discharge (Q_T), and effective discharge volume (V_E)

$$B = a\ V_E^{\ b}\,(Q_P/Q_T)^{\ c} \qquad [2]$$

where a, b, and c are empirical coefficients for the mountain stream in Switzerland. In our study, [2] was log-transformed and then step-wise regression selection (with the Bonferroni procedure) was conducted to evaluate the importance of parameters for estimating bedload transport ($\alpha = 0.05$). Although Rikennmann [1997] presented that total bedload sediment yield was correlated to total effective volumes, threshold discharges, and peak discharges, we found that either ratio of peak discharges and threshold discharge (Q_P/Q_T) or effective discharge volume (V_E) was only significant in four streams (Table 4.3). Peak discharge was significantly related to total bedload yield in the LS, YA, and CC channels (Table 4.3, Figure 4.3). Volume of bedload transport was only significantly correlated to effective discharge volume in the OG channel (Table 4.3). These results imply that instantaneous stream power is important for the entrainment of bedload in LS, YA, and CC channels. In contrast, the duration of flood events may be more important for sediment transport in the OG channel. Amount of bedload transport increased rapidly until up to 2-times the threshold discharge in the LS and YA channels (Figure 4.3). Therefore, bedload materials may be set in motion rapidly when discharge exceeds the threshold level. However, onset of significant bedload movement in bedload sediment with respect to discharge declined in the CC and OG channels (Figure 4.3). Such findings may imply that channel bed materials were not actively mobilized until the discharge level 2-times the threshold value. Since we did not directly measure bedload sediment during storm events, threshold discharge in the CC and OG channels may have been underestimated.

Amount of bedload sediment with respect to peak discharge differed before and after the largest storm (October 21) in all streams, although each stream exhibited distinct patterns of change. Three to five times more bedload sediment was transported in the LS channel after October 21 for similar peak flows compared to before the storm event (Figure 4.4). Because a small slope failure occurred during the October 21 event, sediment that was produced by the failure was stored in and around channels and remobilized after the storm. In the YA channel, however, the amount of sediment deposited at the weir decreased after the largest discharge on October 21 (Figure 4.4). Because there was no significant new sediment source in the upper reaches of YA, most of the available material in the channel was already transported, and the sediment supply may have been exhausted. Such declines in bedload transport due to exhaustion of sediment supplies throughout the storm season have been observed in a mountain stream in Alberta [Nanson, 1974] and in low gradient channels of Idaho [Moog and Whiting, 1998]. Relatively greater amounts of bedload sediment after the October 21 storm were also found in the OG channel (Figure 4.4). Furthermore, D_{50} of bedload material in the November 1 (13.0 mm) and November 9 (8.5 mm) storms was coarser than during October 21 (6.5 mm). Since no evidence of significant sediment sources from hillslopes and channel beds (e.g., slope failures and collapse of woody debris dams) was found, movement of greater amounts and coarser sediment may be associated with the disruption of the armor layer in the OG channel [Nanson, 1974; Warburton, 1992]. No noticeable changes in bedload sediment were found in the CC channel before and after the highest flow.

Availability of sediment affects the relationships between discharge characteristics (peak flow and effective discharge volume) and the volume of bedload yield during storm events. Bedload sediment availability is affected by: (1) sediment supply from hillslopes to stream channels; (2) sediment exestuation through sequences of storm events [Moog and Whiting, 1998]; and (3) disruption of channel bed conditions during high flows [Sidle, 1988; Adenlof and Wohl, 1994]. Such changes alter the strength of relationships (e.g., multiple regression coefficient) between flow characteristics and amount of bedload sediment. In our study, the small multiple correlation coefficient obtained in the YA channel may imply rather limited sediment supplies (Table 4.3). In contrast, a strong correlation between discharge characteristics and bedload amount was found in LS where sediment was constantly supplied from unvegetated hillslopes. In the previous studies, Sidle [1986] found a strong ($R^2 = 0.80$) relationship between peak bedload transport (kg h^{-1}) and peak discharge for 26 storms in a second-order forest stream in Southeast Alaska. In contrast, Adenlof and Wohl [1994] did not find strong relationships between peak flow and sediment transport. Such differences in multiple correlation coefficients related to sediment supply and antecedent storm conditions for available sediment transport [Nanson, 1976; Sidle, 1986?1988]. If supply of sediment is extremely limited, either a weak or no correlation between discharge characteristics and bedload transport would be expected. For supply-limited conditions, sediment supply may be governed by random factors such as slope failure and collapse of woody debris dams and channel steps [Adenlof and Wohl, 1994]. Hysteresis over seasonal time scales modifies the relationships between discharge and sediment transport throughout monitoring period.

4.4.2. Material composition of bedload sediment

The particle size distribution in bed materials of headwater streams influences bedload entrainment processes. However, theoretically-based sediment transport equations are not typically applicable to such mixed-bed, steep gradient channels because flow depth in channel reaches varies [Rickenmann, 2001; Zimmerman and Church, 2001]. Theoretical sediment transport equations predict that these headwater channels can transport much coarser sediment because of their higher energy gradient. Mean Basal shear stress (τ) can be explained as

$$\tau = \rho\, g\, D\, S \qquad [4]$$

where ρ is density of water in kg m^{-3}, g is acceleration due to gravity (m s^{-2}), D is the depth of flow (m), and S is the water surface gradient estimated as the channel slope (m m^{-1}). Based on the equation

[4], shear stress ranges in our four channels ranged from 132 to 196 N m^{-2} for near threshold discharge. Zimmerman and Church [2001] calculated potential mobile bed sediment based on

$$\tau = \theta \, (\rho_s - \rho) \, g \, D_{84} \qquad [5]$$

where θ is Shields number (0.045 from Zimmerman and Church 2001) ρ_s is particle density of sediment (2650 kg m^{-3}), D_{84} is the substrate diameter that can be mobilized at the shear stress. Using shear stress values derived from [4] for near threshold discharges, theoretical D_{84} of bedload can be back-calculated from [5]. The D_{84} values range from 180 to 270 mm in our streams; these are significantly larger than sampled bedload sediment. Because these equations assume uniform channel geometry, such theoretical approaches are not appropriate to assess the bedload movement in mixed-bed, steep gradient channels that contain woody debris [Adenlof and Wohl, 1994; Zimmerman and Church, 2001]. In addition, particle density of sediment also deferred compared to the equation [5] based on our field measurement (1280 kg m^{-3}).

In all four of our streams, bedload sediment was significantly finer than channel bed substrate. Particle sizes ranging from 1 to 10 mm were the most mobile bedload materials throughout the monitoring period in all four streams (Figure 4.5). D_{50} of bedload sediment was approximately D_5 to D_{15} of the channel bed surface substrate. Particularly, bedload sediment in the LS channel was relatively finer than the other channels, because of fine sediment supply from landslide scour (Figure 4.5). Although D_{50} of subsurface bed materials is typically 50% to 100% finer than that of surface bed materials [e.g., Church and Hassan, 1992; Whiting et al. 1999; Buffington and Montgomery, 1999], D_{50} of bedload sediment in the largest storm on October 21 might be still finer than subsurface D_{50} of our stream channels. Church et al. [1991] also found that particle sizes of bedload sediment were significantly finer than subsurface channel bed material in a gravel bed stream in British Columbia. Consequently, strong selective transport of fine materials more likely occurred in steep headwater channels. Lisle [1995] also found that smaller and steeper channels have tended to have selective transport processes in various streams of the Pacific Northwest.

An alternative hypothesis to the selective transport of bedload sediment is the equal mobility hypothesis that assumes all grain sizes mobilize at approximately the same discharge. Equal mobility occurs because of the hiding effect and the protrusion of large grains over small size fractions cancel the mobility of smaller size classes during the earlier stage of flood events [Parker et al., 1982]. Equal mobility may be applicable in lower gradient and gravel bed channels because the variation of channel bed subsurface substrate is smaller [Lisle, 1995]. In addition, changes in selective transport relative to equal mobility may occur with increasing discharge. For instance, Campbell and Sidle [1985] found that the size distribution of bedload sediment during the largest storm event in the season was identical to channel bed substrate in a southeast Alaskan stream. Rickenmann et al. [1998] noted that equal mobility might occur when the peak discharge was from 2 to 3 times higher than the threshold discharge because of significant increases in transported bedload sediment size in steep (18%) channels. Typically, the breakup of armor layers entrain both fine and coarse particles: this in turn appears to support equal mobility. Church et al. [1991] observed that equal mobility only occurred for the sand fraction of the channel bed material. Consequently, differences between equal mobility and selective transport may relate to variation of substrate sizes, supply conditions of sediment (e.g., limited or supply of sand), and discharge characteristics relative to channel bed substrate.

Sediment supply and discharge conditions affected the nature of material transport in all four streams. In the LS channel, greater amounts of fine sediment (diameter: 1 to 11.2 mm) compared to coarse material (diameter > 11.2 mm) were transported during all storms except the largest event (October 21). Because sand and fine gravel were continuously supplied from adjacent unvegetated hillslopes, "nonequilibrium" conditions between sediment supply and transport capacity may have occurred in LS. Indeed, greater amounts of fine sediment accumulated in the LS and these fine materials were dominantly transported. In the YA, CC, and OG channels, however, more fine material was transported than coarse material during large storms with peak discharge > 4-times the threshold discharge (Figure 4.6). Therefore, changes in dominant bedload sediment from fine (1 to 10 mm) to coarse (>10 mm) occurred during larger events in the YA, CC, and OG channels.

In addition to sediment supply conditions, large variations in channel bed substrate size cause selective bedload transport [Lisle, 1995]. Particularly, channel obstructions formed by interlocked boulders and cobbles (> 200 mm in diameter) and woody debris influence entrainment of bedload materials and stability of channels: this in turn affects selective transport processes in headwater channels. Channel steps formed by larger particles (Figure 4.5) are typically stable and decrease local channel [Church et al., 1998; Zimmerman and Church, 2001]. Woody debris also creates sediment storage sites [Gomi et al., 2001] and may alter the threshold for bedload entrainment. Although channel structures in LS were destroyed during the mass movement in 1993, we found that boulder steps had been formed 5 years after the disturbance. Because no significant changes in formation and disruption of boulders and woody debris steps were found at any of the monitoring sites during the autumn storm season, smaller stored bedload particles (sand and gravel) were likely selectively entrained from behind boulders and woody debris dams [Adenlof and Wohl, 1994; Lisle, 1995; Whiting et al., 1999]. Such channel obstructions cause lower transport efficiency especially in small and steep channels [Rickenmann, 2001]. Therefore, fine sand and fine gravel (diameters 1 to 10 mm) were the dominant bedload sizes. This material was transported over channel steps during the most storm events, while substrate materials > 200 mm were not mobilized based on field observations and surveys. Most of the stream substrate > 200 mm (e.g., cobbles and boulders) may be transported by more extreme events such as mass movement [Sidle, 1988; Grant et al. 1990]. Median size of substrate (diameters 10 to 200 mm) may be mobile during intermediate flood events [Zimmerman and Church, 2001]. Movement and behavior of such size classes were examined using bedload tracers (see next section).

4.4.3. Movement of bedload tracers

Channel bed materials with diameters ranging from 10 to 200 mm were transported less frequently than most of the bedload materials. Bedload tracers (mean diameter ranging from 28 to 30 mm) placed in the four streams on September 16, 1999, were mobile three times during the monitoring season. Threshold discharge for movement of bedload tracers ranged from 12.0 to 22.0 $\times 10^3$ m^3 s^{-1}, approximately 2- to 4-fold the threshold discharge for bedload sediment (Table 4.1). Recovery percentage of tracers ranged from 20 to 100% in the monitored channels. Some tracers were buried in the channel bed and in woody debris jams. Gintz et al. [1996] noted that bed surface particles in the range from D_{30} to D_{70} were mobile once every year in a mountain stream in Germany. During storm events with > 4-fold threshold discharge in the YA, CC, and OG channels, larger amounts of bedload sediment with diameters >10 mm were sampled compared to finer (1 to 10 mm) bedload sediment (Figure 4.6). Consequently, based on the tracer study and sampled bedload sediment, coarser materials (10 to 200 mm) were actively mobilized only during peak flows that were 2 to 4 times the threshold discharge for bedload transport.

The average displacement distance of bedload tracers varied among streams and between monitoring sites (Table 4.4). Distance of bedload tracer movement did not relate to discharge characteristics. O'Conner [1993] found that no significant relationships between travel distances and tracer diameters in steep headwater channels in Washington. Therefore, the movement of channel bed materials in the range of D_{30} to D_{50} may be governed by more random, local conditions, and obstructions such as channel steps and woody debris. Because of the recruitment of logging slash, most of the tracers in the CC channel deposited in the channel steps and in log jams formed by LWD and FWD (Figure 4.7). No tracers from the upper monitoring section (M2) of CC moved downstream, possibly because the tracers were installed on the top of a woody debris step. Commandeur et al. [1996] and Beechie [2001] also found that changes in amount of woody debris related to mass movement and timber harvesting are important factors for trapping sediment. Because of the regeneration of alder in the riparian zone of YA after landslides in 1962, relatively greater percentages of tracers were trapped behind LWD in YA compared to LS (Figure 4.7). Compareing to CC and YA channels, many of the tracers placed in OG stream deposited behind boulders.

The condition of the channel bed surface is related to sediment supply; this condition also serves to modify the transport distance of bedload sediment. Bedload tracers were mobile for longer distances on the smooth channel bed of LS due to fine sediment inputs and less woody debris in the channel (Table 4.4). Because fine sediment was consistently supplied to the LS channel due to sheet and rain splash erosion, transport capacity was somewhat overwhelmed by high sediment supplies, thus causing fine sediment deposition and creating smoother bed surfaces [Dietrich et al., 1989; Buffington and Montgomery, 1999b]. A large supply of fine sediment causes fining of the channel bed surface and a reduction of pool depth [Lisle and Hilton, 1992]. Therefore, greater bed smoothness due to fine sediment supply may increase transport distance of particles in the LS channels. In contrast, pools, bedrock pockets, and spaces (pockets) between cobbles and boulders may retain bedload materials during supply-limited conditions in YA, CC, and OG channels (Figure 4.7). Bedload materials can be buried between larger cobbles and boulders and effectively 'hidden' from the stream flow [Church and Hassan, 1992]. Consequently, complexity created by woody debris and boulders modifies the transport distance of bedload tracers. (Needs more work in this section).

4.5. Suspended sediment response and yield

Suspended sediment transport response varies among different stream types. Availability of suspended sediment in stream channels affects the response with stream discharge (Figure 4.8). A significant relationship between discharge and suspended sediment concentrations was found only in the LS channel during the 1999 storm season. In the LS channel, suspended sediment concentrations remained high throughout the storm season probably due to the sediment supply from the stream banks and hillslopes. The greater variation of suspended sediment concentrations in the YA, CC, and OG channels related to changes in sources of suspended sediment and antecedent storm events [Nanson, 1974; Sidle and Campbell, 1985] (Figure 4.8). In the YA and OG channels, slopes of SS concentration versus discharge progressively decreased through autumn storm season (Figure 4.8) because availability of fine sediment in and around the channel decreased with progressively. The relationships between SS concentrations and discharge were not significant in the CC channel, possibly due to sudden and sporadic releases of fine sediment from behind woody debris.

Total suspended sediment yield was calculated for selected storm events. Suspended sediment contributed only 4.2 to 45.1% of the total sediment yield in the CC and OG channels. Higher contributions from suspended sediment to total sediment yield consistently occurred in the LS channel (range: 65.0 to 75.6%). The percentages of suspended sediment increased from 27.3 to 69.1% in the YA channel because of the exhaustion of the bedload sediment supply late in the storm season. O'Connor [1993] estimated that suspended sediment comprised 69% of the total sediment yield in steep forest streams in the Olympic Peninsula, Washington. Lenzi and Marchi [2000] estimated that suspended sediment concentration comprised 16 to 100 % in total sediment yield. These large variations in the percentages of suspended sediment are affected by sediment sources and the amount of bedload, particularly the instantaneous supply from the slope and the channel bed [Grant and Wolff, 1991; Lenzi and Marchi, 2000]

4.6. Characteristics of sediment transport in headwater streams

Patterns of sediment transport in steep-gradient headwater channels can be characterized by relationships between dominant mobile materials and peak discharges of storms. Four size classes of channel bed sediment – fine (diameter < 1mm: suspended sediment), small (diameter ranging from 1 to 10 mm), medium (diameter ranging from 10 to 200 mm), and large (diameter > 200 mm) – characterize different transport regimes. Occurrences of seasonal hysteresis of bedload and suspended sediment transport depend on exhaustion of in-channel sediment and supply of sediment from hillslopes (e.g., slope failures) and the channel bed (e.g., disrupted armored layer and collapsed debris dams). Phases of bedload sediment transport with changing stream discharge in steep gradient headwater channels can be explained in slightly different ways compared to models of Jackson and Beschta [1982] and Warburton [1992]:

Before phase 1: Fine sediment < 1mm (clay, silt, and fine sand) may be entrained as suspended sediment before movement of bedload sediment. Amount and concentrations of suspended sediment transport in headwater channels depended on sediment supply from hillslopes to channels.

Phase 1: Channel bed materials ranging from 1 to 10 mm are most actively mobile as bedload sediment during low stormflow events in steep headwater streams. Such materials may be mobilized five to ten times during a storm season and are transported long distances over channel steps and woody debris dams. Therefore, selective transport was most notably observed during events with recurrence intervals < 1.5 years (i.e., approximately bankfull discharge) [Lisle, 1995]. Because of the constant supply of sand and fine gravels from adjacent hillslopes, fine sediment is the more dominant bedload material that contributes to the abundant sediment supply in disturbed channels (e.g., LS channel).

Phase 2: Channel bed materials ranging from 10 to 200 mm are gradually mobilized with discharge levels approaching recurrence intervals of 1.5 years; these transported materials remain finer than step forming materials (boulders and cobbles). Such materials may be moved only once or up to several times during a storm season. The entrainment of the medium particles is governed by more random factors such as local turbulence and roughness elements [O'Conner, 1993; Gintz et al. 1996]. Moreover, transport distance of the materials depends on channel smoothness related to sediment supply conditions and roughness elements within the channels (e.g., woody debris and boulders). Disruptions of the armor layer and sudden sediment inputs (due to slope failures and LWD dam collapse) may produce greater amounts of sediment during greater events [Sidle, 1988; Warburton, 1992; Adenlof and Wohl, 1994].

Phase 3: All channel bed parietals may only be mobilized during mass movement events, because channel bed substrate > 200mm in diameter may remain stable until mass movement occurs [Sidle, 1988; Grant et al. 1990]. Interlocking structures of boulders and cobbles in the channel form steps and alter channel stability [Zimmerman and Church, 2001]. Large woody debris dams and jams are also stable until wood decomposes or they are destroyed by mass movements. Aggregation of large woody debris and resulting formation of channel obstructions is important for understanding sediment accumulation in headwater channels.

In addition to the overall characteristics that were observed in the four streams, the occurrence of mass movement and the vegetation recovery induces variations in sediment transport in headwater channels. Depending on the timing of and recovery from disturbances, bedload and suspended sediment yield in steep-gradient headwater channels is controlled by linkages between channels and hillslopes that affect the amount of woody debris, sediment supply, and transport capacity. Our findings in relation to sediment movement in LS and YA channels can be arranged chronologically after the occurrence of mass movement. Regenerating riparian vegetation produces organic matter, reduces surface erosion, and increases the infiltration capacity of soils: this retards sediment delivery from bank slopes and consequently decreases sediment supply. Because regenerated riparian stands produce woody debris, larger amounts of in-channel LWD and FWD were found in the YA channel than in the LS channel (Table 4.1; Figure 4.9a) [Gomi et al., 2001]. Therefore, more sediment was stored behind woody debris in the YA channel compared to the LS stream (Figure 4.9b). Despite the greater sediment storage in YA compared to OG, the amount of bedload sediment transported in YA was similar to bedload mass in OG (Figure 4.2 and 4.3).

Timber harvesting and related woody debris recruitment also contribute to variations in sediment transport processes. Larger amounts of LWD and FWD were found in the CC channel; such woody debris may increase channel roughness and temporally store and trap sediment (Figures 4.7 and 4.9). Because of smaller width of the CC channel (Table 4.1), woody debris related to logging activities is more stable compared to larger streams [Millard, 2000]. Removal of such logging slash significantly increased sediment transport in a headwater stream in British Columbia [Commandeur et al., 1996].

4.7. Summary and conclusion

Four streams with different management and disturbance regimes exhibited different sediment transport responses. External influences such as mass movement and timber harvesting greatly modified sediment entrainment, transport processes, and storage of sediment because these factors affect *inputs* of sediment and woody debris and coupling between hillslopes and streams. Sediment dynamics in steep-gradient headwater channels are characterized as follows: (1) peak flow significantly altered the amount of bedload transported in all streams; (2) seasonal hysteresis in bedload transport occurred during the autumn storm season, depending on sediment exhaustion, sudden sediment supply from bank failures, and disruptions in the bed armor; (3) transported bedload was smaller than channel bed substrate in all streams because much of the larger substrate contributed to rather stable interlocked channel structures; (4) bedload transport distance may have been affected by relative channel smoothness related to the amount of woody debris and fine sediment supply conditions due to previous history of mass wasting; (5) the occurrence of mass movements (extreme events) and related recovery processes modify the background level of sediment availability and the thresholds for entrainment of sediment; (6) recruitment of logging slash affects sediment storage and transport; and (7) spatial and temporal variations of sediment movement are largely related to supplies of sediment and woody debris as well as sediment storage within channels; these processes are associated with linkages among hillslopes, zero-order basins, and stream channels.

Since headwater streams are important sources of sediment, water, nutrients, and organic matter to downstream systems, knowledge of temporal and spatial variations of sediment transport in these systems related to mass movement and timber harvesting can improve our understanding of sediment dynamics within the channel network and its influence on stream ecosystems. Information on sediment movement in headwater stream needs to be integrated into management and restoration schemes for larger stream ecosystems.

Table 4.1 Characteristics of the study sites

	Drainage area (ha)	Mean gradient	Mean bankfull width (m)	Exposed bedrock (%)	Mean discharge (10^{-3} m^3 s^{-1})	Minimum discharge (10^{-3} m^3 s^{-1})	Maximum discharge (10^{-3} m^3 s^{-1})	Threshold discharge (10^{-3} m^3 s^{-1})	
								Bedload movement	Bedload tracers
LS	2.05	0.40 (0.11)	1.2 (0.6)	26.7	2.71 (3.35)	0.60	56.1	3.4	11.2
YA	2.50	0.37 (0.09)	1.1 (0.5)	26.0	5.53 (5.81)	0.92	60.0	5.6	10.6
CC	2.18	0.36 (0.12)	0.9 (0.3)	0.1	5.08 (3.59)	1.65	26.7	5.0	14.5
OG	2.50	0.27 (0.03)	1.2 (0.2)	0.1	8.17 (10.19)	1.09	86.1	5.9	22.0

Surface substrate D_{50} (mm)	Number of LWD ($100m^{-1}$)		Number of FWD ($100m^{-1}$)	Volume of stored sediment (m^3 $100m^{-1}$)	Landslides and debris flows
	Total	In-channel			
35.5	15	4	15	3.1	1993/79
34.5	24	21	41	6.9	1961
30.0	78	58	163	2.3	
53.5	24	23	56	4.3	

Note: Old-growth (OG); recent (3 year old) clear-cut (CC); young-growth (40 year after clear-cutting) alder riparian forest (YA); and recent landslide and debris flow channels (LS).
Standard deviations are expressed in parentheses.
* Mean channel gradient, bankfull width, exposed bedrock, number of LWD and FWD were estimated in channel reaches 200m upstream from weirs.

Table 4.2 Summary of bedload samplings

	LS		YA		CC		OG	
	Max discharge (10^{-3} m^3 s^{-1})	Bedload (kg)	Max discharge (10^{-3} m^3 s^{-1})	Bedload (kg)	Max discharge (10^{-3} m^3 s^{-1})	Bedload (kg)	Max discharge (10^{-3} m^3 s^{-1})	Bedload (kg)
Sep. 10	6.2 (1)	5.0	10.6 (1)	4.0	12.4 (2)	4.3	23.8 (2)	1.0
Sep. 20	12.0 (1)	15.1	10.6 (1)	7.5	14.5 (1)	2.0	22.0 (1)	0.5
Sep. 25	16.3 (2)	66.8	12.6 (2)	24.0	18.1 (2)	3.0	37.2 (3)	1.4
Oct. 8	5.6 (1)	3.2	6.6(1)	1.3	12.4 (3)	2.0	15.6 (2)	0.8
Oct. 15	6.1 (2)	3.0	8.9 (2)	1.4	13.5 (2)	3.1		-
Oct. 25	56.1 (2)	1080.4	60.0 (4)	78.5	29.7 (5)	81.0	86.1 (7)	86.2
Nov. 1	7.2 (3)	21.9	23.7 (2)	3.0	15.7 (2)	3.0	25.0 (2)	7.9
Nov. 4	50.4 (1)	708.9	55.3 (1)	9.8	-	-	-	-
Nov. 9	-	-	-	-	19.4 (3)	6.6	79.8 (2)	23.1
Nov. 14	4.7 (3)	13.6	18.9 (3)	4.8	14.5 (2)	1.5	16.7 (2)	1.6

The number of peak flows exceeding threshold discharges is expressed in parentheses.

Table 4.3 Empirical relations of bed load transport

	Peak discharge/threshold discharge		Effective discharge volume	
LS	$B = 0.92\ (Q_P/Q_T)^{2.20}$	$R^2 = 0.89$, $p < 0.001$		
YA	$B = 0.71\ (Q_P/Q_T)^{1.33}$	$R^2 = 0.46$, $p = 0.046$		
CC	$B = 0.03\ (Q_P/Q_T)^{3.69}$	$R^2 = 0.73$, $p = 0.003$		
OG			$B = 0.04 \times 10^{-4} V_E^{1.61}$	$R^2 = 0.79$, $p = 0.003$

Significant independent variables were selected based on step-wise selection with Bonferroni procedure.

Table 4.4 Summary for the movement of bedload tracers

		Mean diameter of tracers (mm)	September 30, 1999			October 26, 1999			November 5, 1999		
			Max discharge (10^{-3} m^3 s^{-1})	Percent Recovered	Mean distance of displacement (m)	Max discharge (10^{-3} m^3 s^{-1})	Percent recovered	Mean distance of displacement (m)	Max discharge (10^{-3} m^3 s^{-1})	Percent recovered	Mean distance of displacement (m)
LS	M1	28.4 (4.6)	16.2	90	2.46	56.1	46	53.79	50.4	-	-
	M2	29.2 (4.7)		60	1.31		20	78.37		20	44.63
YA	M1	28.5 (4.8)	12.6	98	0.34	60.0	66	0.80	55.3	66	0.69
	M2	29.7 (4.2)		100	1.46		42	2.59		32	3.04
CC	M1	29.4 (4.1)	18.1	98	0.55	26.7	86	0.97	19.4	58	1.18
	M2	29.0 (4.3)		96	0		94	0		94	0
OG	M1	30.2 (3.9)	37.2	44	0.51	86.1	82	1.49	79.8	82	2.55
	M2	29.1 (3.9)		48	0.90		68	3.36		72	3.63

Bedload tracers were installed on September 16, 1999 at all sections.
Average distance of movement was calculated using only moved particles.

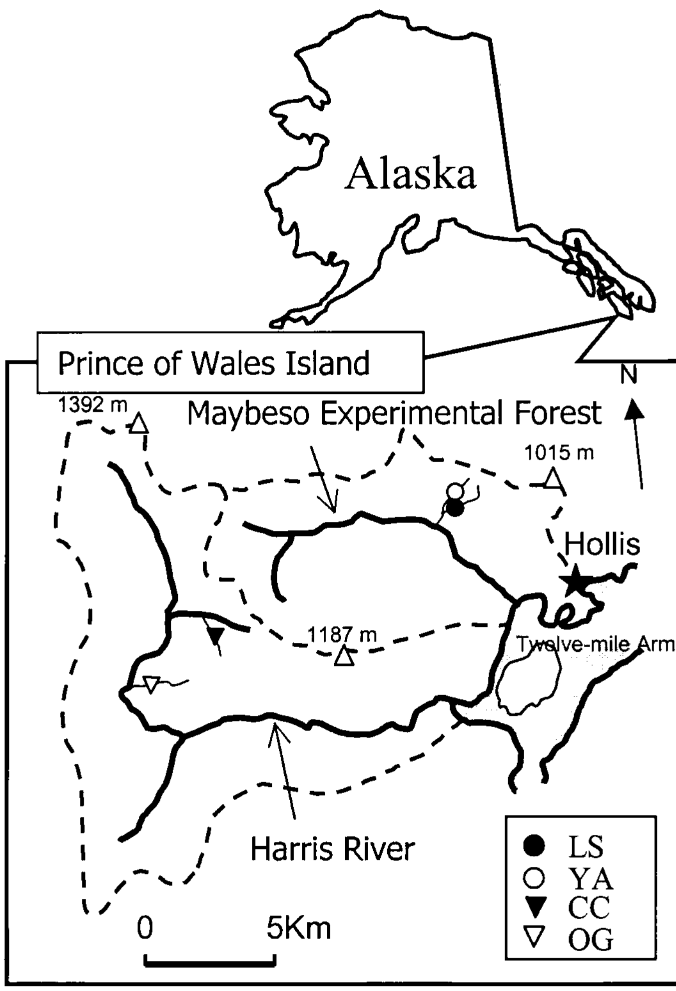


Figure 4.1 Location of study sites in headwater streams of Maybeso Experimental Forest and the Harris river basin. Broken line shows watershed boundary. See Table 1 for definitions of the stream codes.

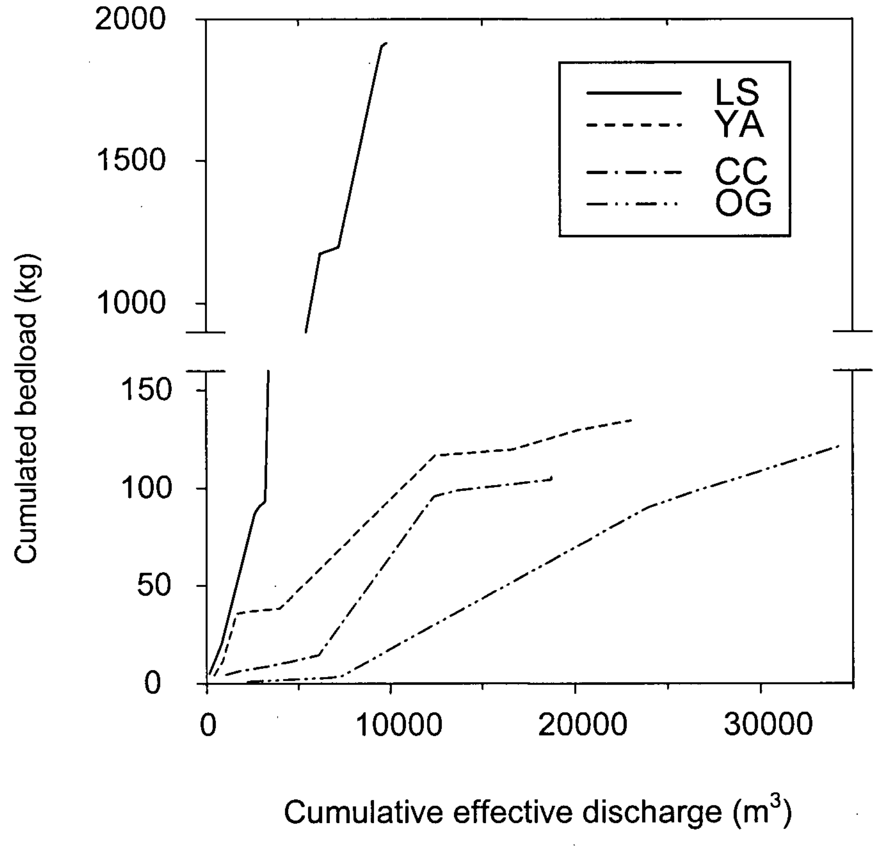


Figure 4.2 Cumulative bedload movement versus cumulative effective discharge volume. Total discharge was subtracted from threshold discharge to estimate effective discharge. LS channels constantly transport greater amount of bedload throughout the monitoring periods.

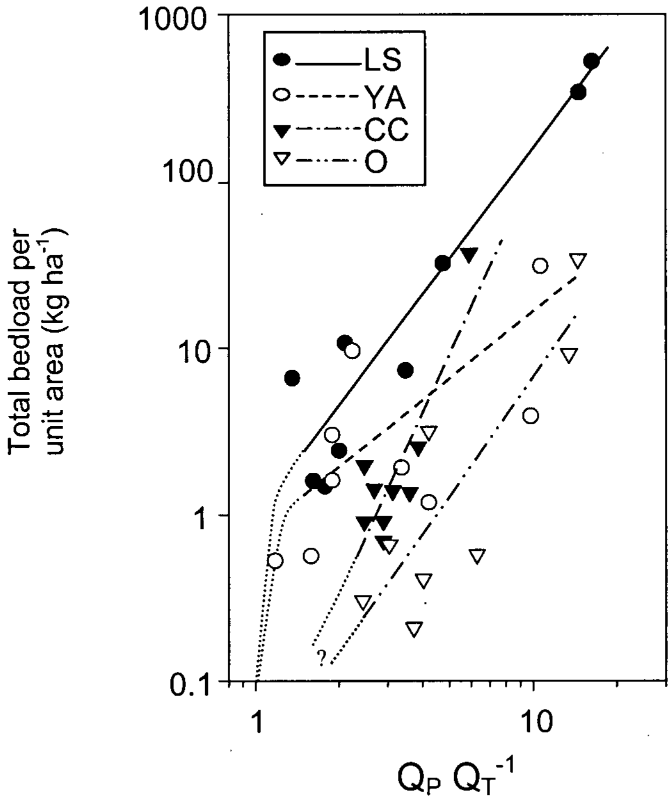


Figure 4.3 Unit area bedload per flood event (B: kg/ha) in relation to peak discharge (Q_P: m^3/s). Dotted lines show approximate relations form threshold discharges. Thresholds discharges in the CC and OG channels may possibly be underestimated based on the figures.

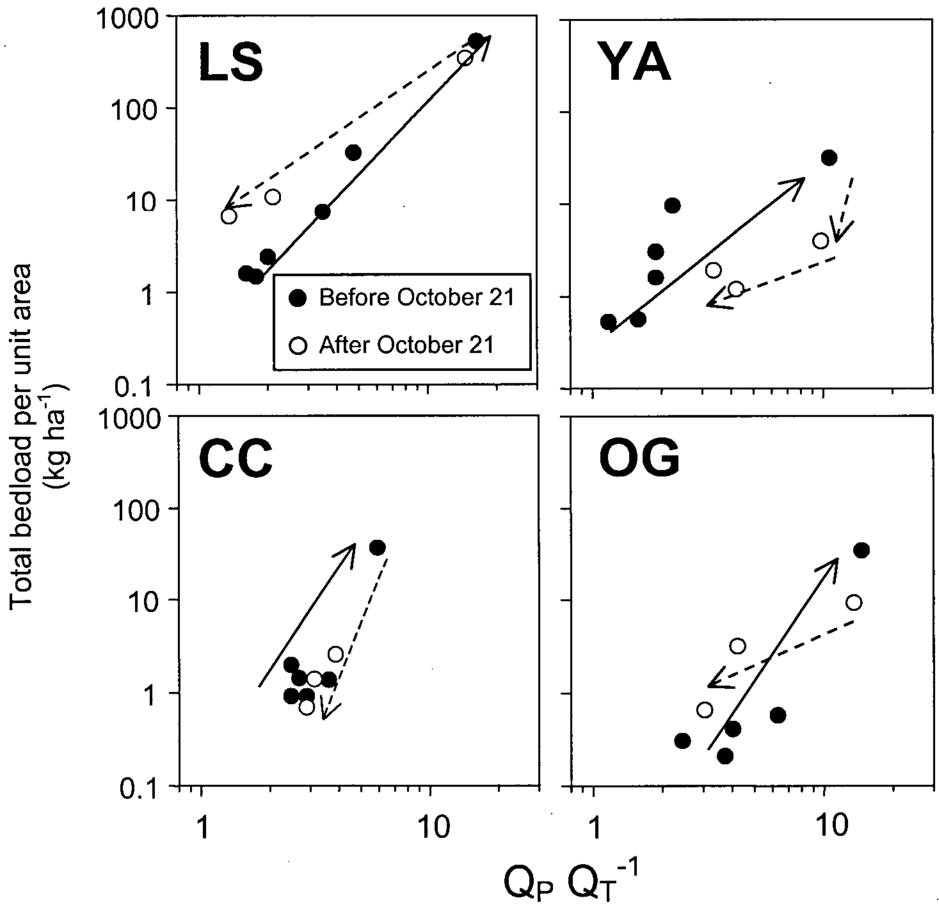


Figure 4.4 Total bedload in flood events related to peak discharge before and after annual peak discharge on October 21. The recurrence interval of the largest storm event on October 21 was 1.5 years based on 20 years precipitation data collected at Hollis. Greater bedload sediment was transported after the largest storm events compared to the same discharge level before the storm.

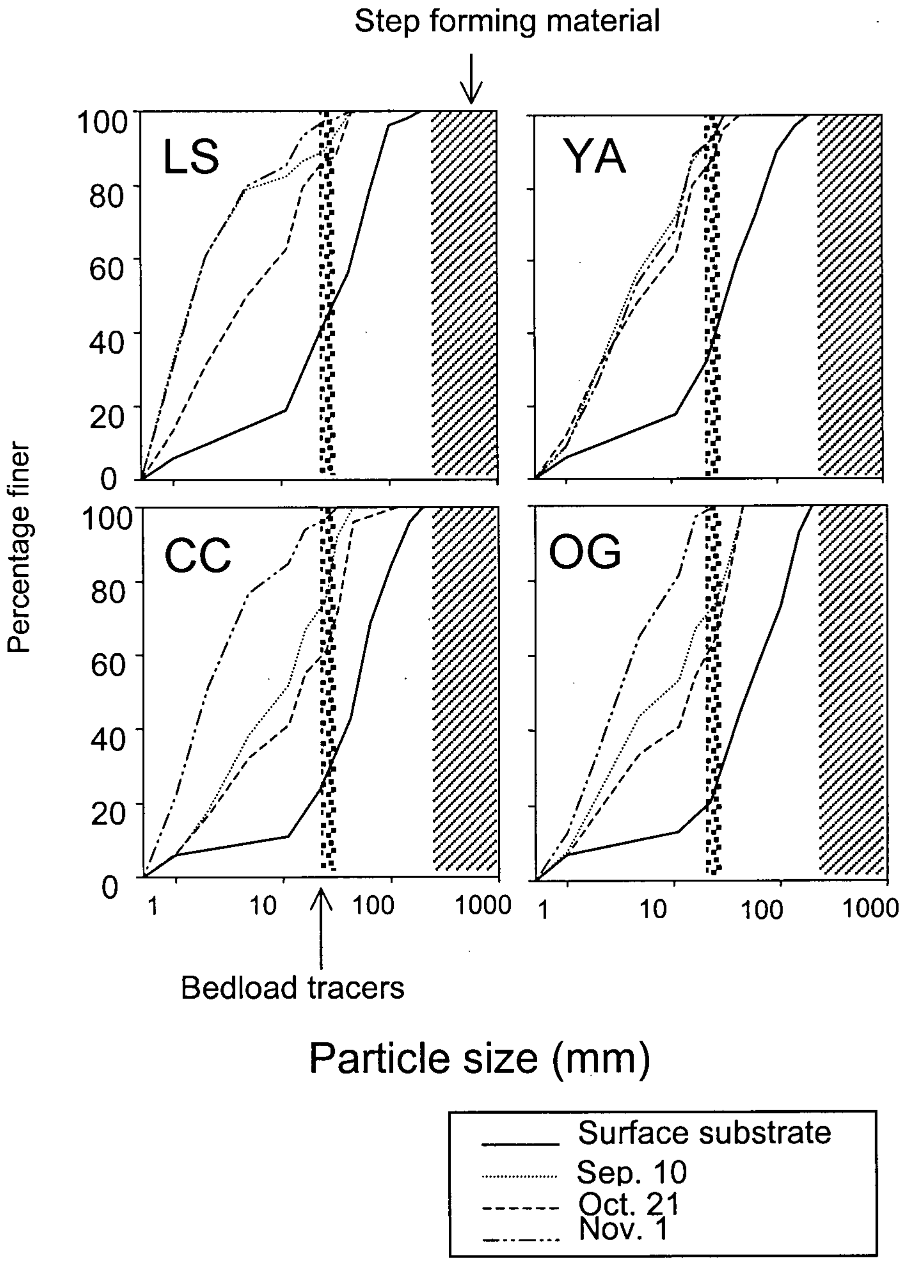


Figure 4.5 Particle size distribution of surface channel bed substrate and bedload sediment in selected storm events. Streambed substrates larger than 200 mm were excluded because of their relative immobility. Inter locking structure of cobbles and boulders (> 200 mm) contribute to form channel steps, storing sediment, and controlling stability of channels [Zimmermann and Church, 2001]. Diameter of bedload tracers ranged from D_{30} to D_{50} of channel bed surface substrate.

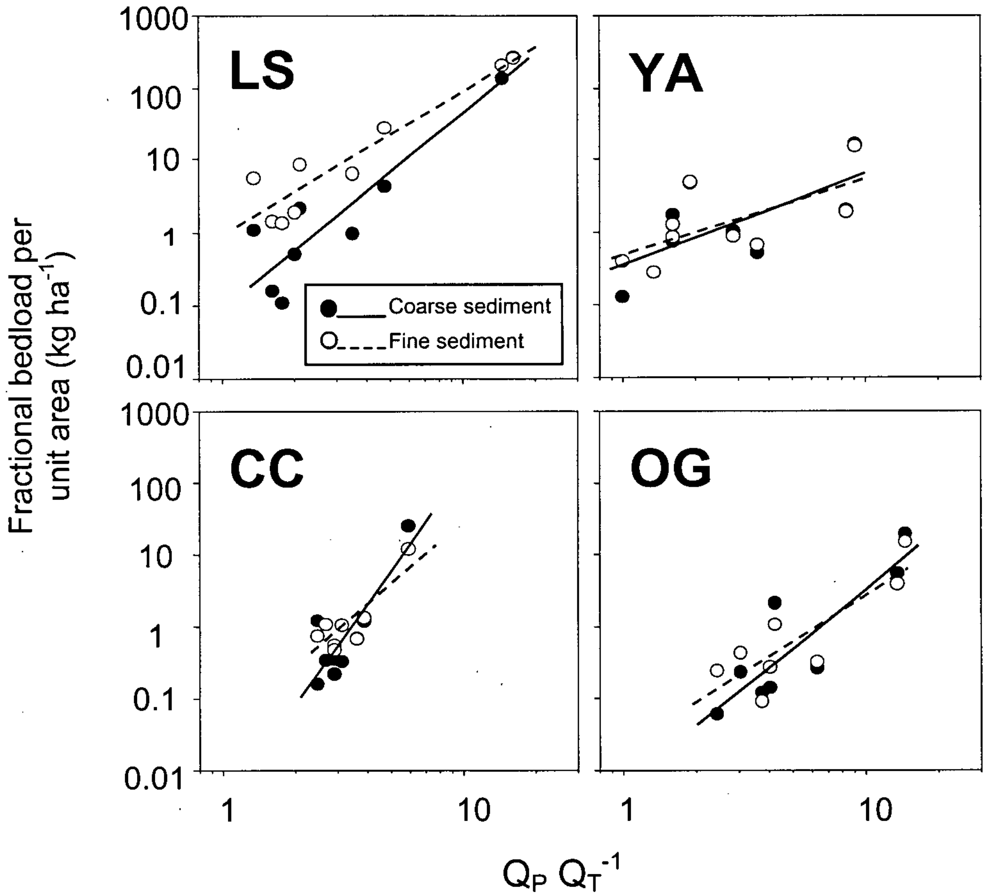


Figure 4.6 Fractional (fine and coarse) bedload transport related to peak discharges. Bedload sediment ranging from 1 mm to 11.2 mm was categorized as fine sediment. Bedload sediment > 11.2 were categorized as coarse materials. All regression lines were significant at confidence level α = 0.05 except fine material in the YA channel ($p = 0.051$).

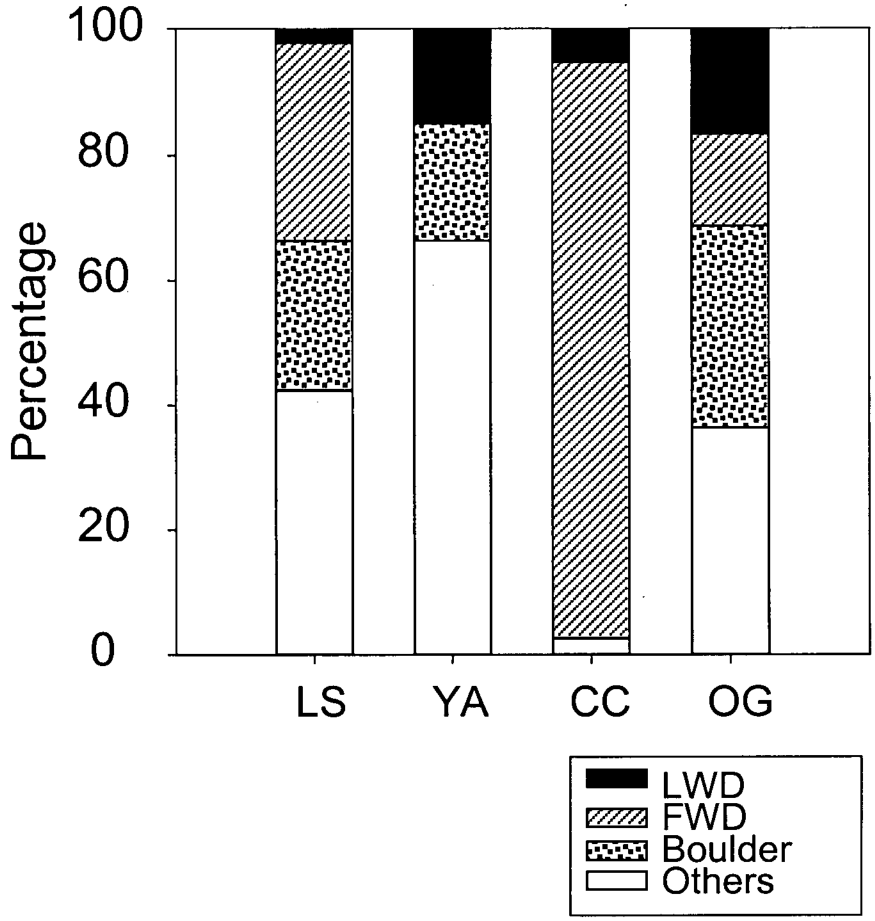


Figure 4.7 Deposited locations of bedload tracers. LWD: tracers deposited in the top and bottom of LWD jams. FWD: tracers deposited in the top and bottom of fine woody debris jams. Boulders: tracers deposited boulder pockets and steps. Others: tracers deposited in mid channel bed or in channel bank.

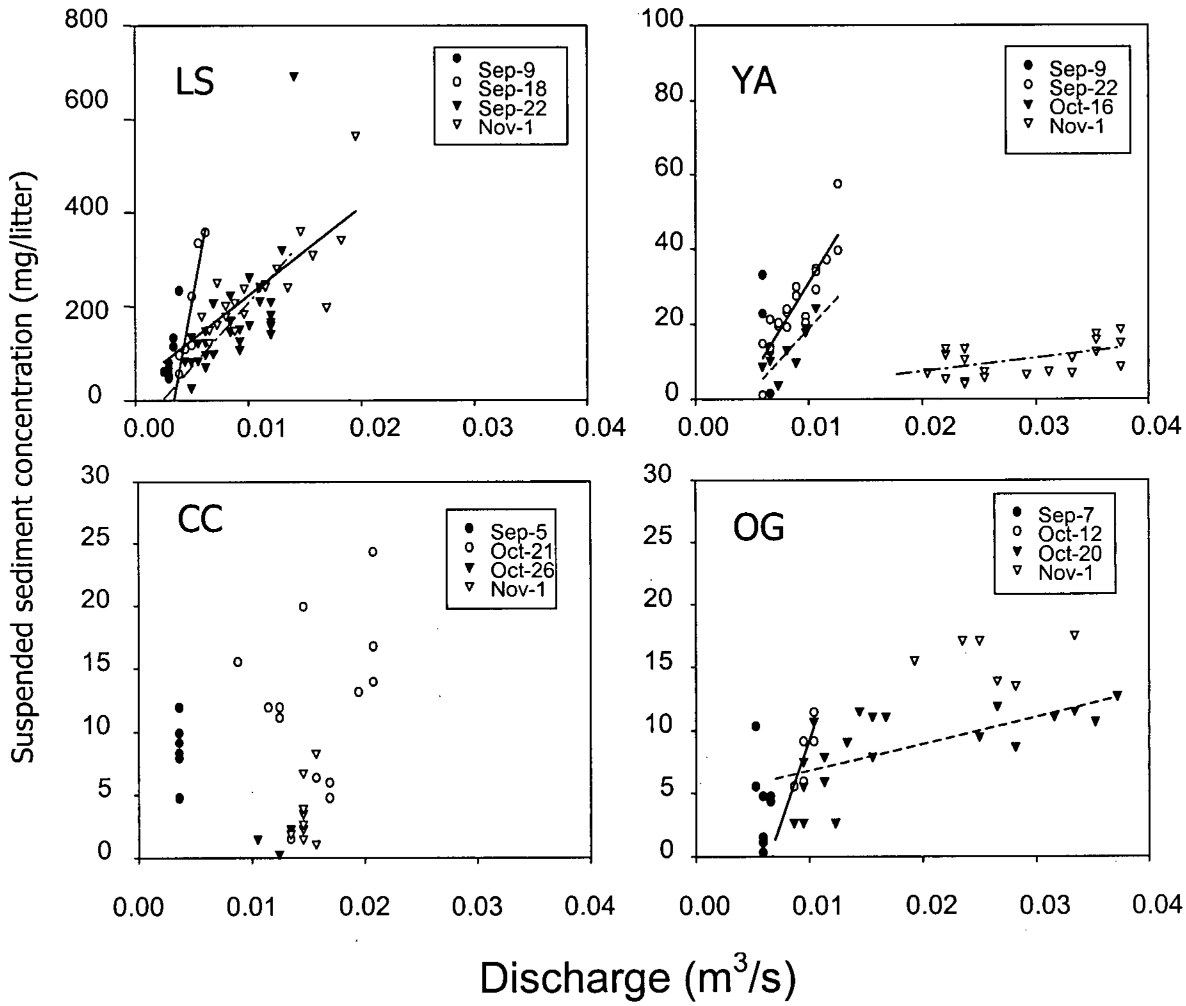


Figure 4.8 Seasonal changes in relationships between suspended sediment concentration and discharge during the rising rim of selected storm events. Significant regressions at $\alpha = 0.05$ were shown in this figure. Scales in discharge vary among streams.

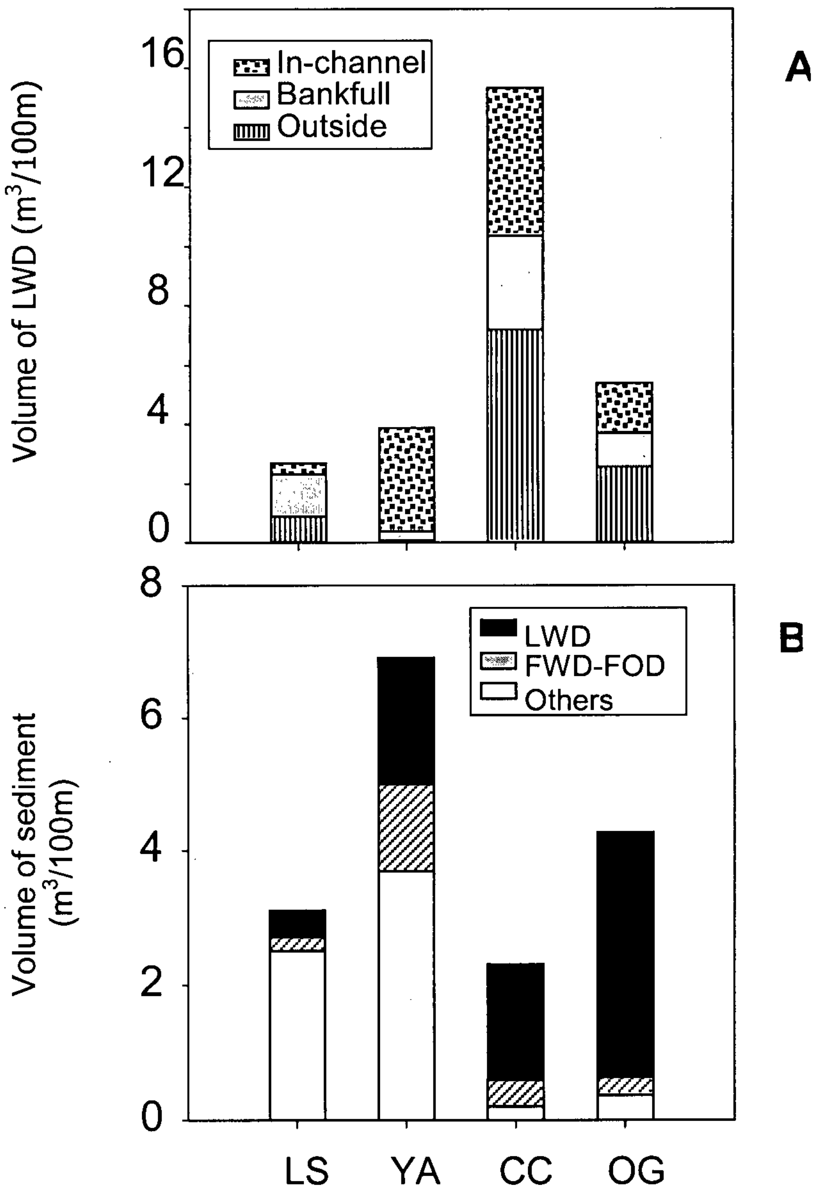


Figure 4.9 Volume of LWD (A) and sediment storage (B) per unit channel length in headwater streams. In channel: the volume of LWD located within the wetted channel width that significantly affects flow dissipation and sediment transport. Bankfull area: the volume of LWD located within the bankfull width, which was defined by the absence of vegetation. Outside: the volume of the terrestrial portion of LWD located outside of bankfull width. LWD: large woody debris formed sediment storage; FWD-FOD: fine woody debris and fine organic debris formed sediment storage; others: rock and bedrock formed sediment storage.

Chapter 5

Hydrogeomorphic linkages of headwater streams

5.1. Introduction

Various hydrological processes and topographic attributes govern hydrogeomorphic linkages in headwater systems. The frequency of storm events influences the timing, magnitude, and spatial distribution of runoff processes, and resulting sediment transport and deposition from hillslopes to channels and from headwaters to downstream reaches (Dunne, 1991; Dhakal and Sidle, *in press*). Subsurface and groundwater hydrology alters the stability of hillslopes and zero-order basins (Tsukamoto et al., 1982), and thus relates to the initiation of landslides that are dominant geomorphic processes in the Pacific Northwest (Sidle et al., 1985). Sediment produced by landslides is transported to downstream reaches as channelized debris flows. Transport distances of sediment depend on tributary junctions, channel gradient, valley configuration, and formation of log jams (Nakamura, 1986; Benda and Cundy, 1990, Hogan et al., 1998); these in turns affect sediment transport and storage throughout channel networks (Wolman; 1977; Benda and Dunne, 1997a; 1997b).

Bedload and suspended sediment transport in steep-gradient headwater streams largely depends on the occurrence of mass movement and their recovery processes (Grant and Wolff, 1991). Sources of bedload and suspended sediment are small bank failures, bank erosion, surface erosion due to rain splash, sheet erosion, and soil creep (Dietrich and Dunne, 1978). Availability of sediment is modified with changes in vegetation coverage and riparian stand regeneration after mass movement (Gomi et al., 2001). Vegetation cover in scour zones of landslides and debris flows reduce the coupling between hillslopes and streams (Shimokawa, 1984). Regenerated riparian stands contribute to the recruitment of woody debris: such woody debris creates sites for sediment storage (Gomi et al., 2001).

Timber harvesting and logging roads affect the hydrogeomorphic linkages in headwater streams. The probability of mass movement increases because root strength decreases 3 to 15 years after timber harvesting (Sidle et al., 1985). Roads intercept precipitation and subsurface flow from hillslopes, and thus modify flow pathways (Sidle et al., *in press*). Because of topographic changes, logging roads both intercept and initiate debris flows and failures (Wemple et al., 2001). Logging slash provides temporary sites for storage of sediment in small headwater streams after clear-cutting (Gomi et al., 2001; Sidle et al., *in press*). In contrast, decreases in the number of woody debris dams due to riparian vegetation removal increase sediment movement (Likens and Bilby, 1982).

Spatial and temporal variation in sediment transport occurs due to changes in the amount of sediment and woody debris related to timber harvesting, the occurrence of mass movement, and the vegetation recovery processes (e.g., Shimokawa, 1984; Grant and Wolff, 1991; Benda and Dunne, 1997a). Wolman (1977) pointed out the importance of linkages among source areas, storage, and transport for understanding sediment routing processes in channel networks. Sediment transport from hillslopes to channels and in-channel storage has been extensively studied for understanding dynamics of materials and impacts of timber harvesting on stream ecosystems in British Columbia, Oregon, Washington, and Japan (e.g., Dietrich and Dunne, 1978; Nakamura et al., 1995; Benda and Dunne, 1997b; Slaymaker, 2000). Although failure initiation and mass movement processes have been investigated in southeast Alaska (e.g., Swanston, 1970; Johnson et al., 2000), few studies had demonstrated sediment transport and storage within headwater streams and from headwaters to downstream reaches of U-shaped glaciated valleys. In particular, sediment movement in such landforms may be unique in terms of linkages from hillslopes to streams and from headwaters to downstream reaches compared to unglaciated terrain of Oregon and Washington. Indeed, because hillslopes, zero-order basins, and channels are tightly coupled in headwater streams (Sidle et al., 2000), timber harvesting and mass movement strongly affect sediment supply, transport, and storage. This study thus focused on documenting sediment routing processes such as transport and storage in headwater systems, particularly related to the occurrence of mass movement and vegetation recovery after timber harvesting in a southeast Alaskan watershed. The objectives of this study are: (1) to describe sediment transport and storage due to episodic mass movement and more regular bedload and suspended sediment movement; and (2) to demonstrate hydrogeomorphic linkages between headwater streams and downstream systems for various sediment movement conditions.

5.2. Study sites

This study was conducted in the Maybeso Experimental Forest within the Tongass National Forest, on Prince of Wales Island, southeast Alaska (Figure 5.1). Drainage area of Maybeso watershed is 39 km^2. About 25 % of the watershed (10 km^2) was logged from 1953 to 1957 using cable yarding methods. Riparian corridors along the main stem of Maybeso Creek and its tributaries were also logged during that period (Bryant, 1980). Logging residue was not removed from streams and slash burning was not conducted after harvesting. The Maybeso Experimental Forest was established to monitor the effects of watershed-wide logging on soil erosion, fish and wildlife habitat, and forest stand succession. The climate in this area is cool and temperate. The mean annual temperature is 10°C and the mean annual precipitation is 2800 mm. The basin is characterized by a U-shaped glaciated valley covered by a veneer of glacial clay-rich till of varying thickness below 1000 m elevation (Swanston, 1970). Major geologic units are metasedimentary mudstones, greywackes, shales, slates, diorite, and granodiorite (Johnson et al., 2000). Dominant riparian forest vegetation includes western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), western red cedar (*Thuja plicata*) and red alder (*Alnus rubra*). Occurrence of alder in riparian zones is highly influenced by past disturbance events such as landslides and debris flows. Resident fish populations in the lower reaches of headwater streams include cutthroat trout (*Oncorhynchus clarki*) and Dolly Varden (*Salvelinus malma*).

Two stream types were selected based on the history of mass movement and riparian stand conditions. Young growth alder [mean diameter at breast height (DBH): 0.2 m] dominated riparian zones in streams affected by mass movement in 1962 (one case in 1979): this type of stream was identified as YA. Small alder stands (mean DBH: 0.03 m) or partially bare slopes were observed in riparian corridors affected by recent landslides (1993): this type of stream was identified as LS (Table 5.1; Figure 5.1). Three headwater streams were investigated in both LS and YA channels. All streams in LS and YA were affected by timber harvesting, but had different histories of mass movement (Table 5.1). Valley forms of all streams were incised less than < 5 m, typical of sidewalls of U-shaped glaciated valleys. All landslides immediately mobilized into channelized debris flows and deposited in the lower gradient reaches of both the LS and YA channels. Based on field observations of scour and deposition, both LS and YA channels were divided into upper (scour and runout) and lower (deposition) sections (See Figure 2 in Gomi et al., 2000). Scour and run-out zones were combined because of the difficulty of distinguishing these features. The YA1 and LS2 channels joined at the lower reaches of LS1, and the YA3 channel joined to the lower reach of LS3 (Figure 5.1). YA 2 did not join any other channels, because it disappeared in the debris flow deposits downstream. Mean gradients of the headwater channels ranged from 9 to 45%, and mean bankfull widths ranged from 0.6 to 3.7 m. The drainage area at the downstream end of the study reaches ranged from approximately 0.14 to 0.35 km^2 (Table 5.1).

5.3. Methodology

The occurrence and spatial distribution of mass movement after timber harvesting was documented through field surveys and by examining aerial photographs. Aerial photographs taken in 1959 (1:15,840), 1962 (1:15,840), 1980 (1:12,000), and 1998 (1: 63,360) were used to interpret the spatial distribution of landslides and debris flows. Unvegetated slope areas that were formed by either episodic mass movement or more frequent slope failures were mapped and counted. Scour, run-out, and deposition zones of 6 streams in the LS and YA channels were intensively investigated in the field. Stream channels, abandoned channels, and sediment deposition along channels, such as debris fans and terraces were mapped using a tape and compass. Because of different lengths of scour and deposition zones among channels, the length of the surveyed headwater reaches varied from 100 to 400 m in both the upper and lower reaches of the LS and YA streams (Table 5.1). The reference point (0 m point) of the stream survey was the boundary between the scour or run-out and deposition zones of mass movement. Stream gradient and cross-sectional profiles were surveyed using a level, stadia rod, and tapes. Exposed bedrock length and its position in the channel were also measured. The wetted and bankfull widths of streams were estimated every 5 m. Bankfull width was defined by the presence of moss and rooted vegetation along the channel margins and the top of banks.

Locations, number, and volumes of large woody debris pieces (LWD: diameter ≥ 0.1 m, length ≥ 0.5 m) and numbers of fine woody debris pieces (FWD: diameter 0.03 – 0.1 m, length ≥ 0.5 m) were measured and calculated using methods described by Gomi et al. (2001). Fine organic debris (FOD: accumulations of leaves and branches) was also measured, if sediment was stored behind these features. Sediment storage behind woody debris and other obstructions (e.g., boulders and bedrock) was measured based on the geometry of sediment wedge (width, length of the wedge, and average depth at the front of the wedge). Average depth of the sediment wedge was measured using a sediment probe at several points. The cause of sediment deposition was categorized according to the formation elements of the sediment wedge: LWD, FWD, FOD, boulders, and bedrock. The volume of sediment stored behind woody debris and other obstructions was computed based on rectilinear pyramid (Gomi et al., 2001).

The age of sediment deposits was estimated from even-age stands of alder growing in these scour and deposition zones (Nakamura, 1986). Three cross sections in each stream were surveyed to describe valley and channel profiles. Size of mobile streambed material was measured based on the median diameter of 100 pebbles in a 0.2×0.2 m grid at the three cross-sections (Wolman, 1954). Large cobble and boulder components (> 0.2 m) were excluded because of their relative immobility except during landslides and debris flows despite their contribution for the formation of channel steps (Church, 1996). Drainage areas of study streams were measured from a topographic map (USGS Crag C-3) using a digital planimeter.

Bedload and suspended sediment movement was monitored in the LS 1 and YA 1 channels from September to November 1999. V-notch weirs (120°) were installed in LS 1 and YA 1 in the summer of 1999 to measure discharge and sediment yield. Sediment deposited behind the weirs was sampled when significant volumes accumulated, typically after major storm events. Sampled sediment was sieved into size classes of 11.2, 16.0, 25.0, 32.0 45.0, and 115.0 mm, and weighed in the field. Sediment smaller than 11.2 mm was taken back to the laboratory, dried, and then weighed for smaller sieve classes (4.75, 2.00, 1.00, and 0.425 mm). Sub-samples of finer sediment (< 11.2 mm) were burned for 2 hours at 500°C to remove organic matter in each sieve class. The bulk density of the sampled sediment was 1.2 g cm^{-3}.

Suspended sediment samples were collected during selected storm events in the LS1 and YA1 channels with an automated pumping sampler. The intake of the pumping sampler was attached to a metal rod and suspended in mid-stream. This minimized the effects of flow separation and clogging by organic matter for sampling efficiency (Sidle and Campbell, 1985). Sampling was automatically activated at a predetermined storm stage. A 500 ml sample was collected every 10 to 15 minutes. Because only 24 sampling bottles were contained in the sampler, suspended sediment samples were typically only collected during the rising limbs of storms. Samples were transported to the Hollis field station (Figure 5.1) where they were analyzed. Total suspended solids (TSS) were determined by passing a known volume of stream water through a glass fiber filter with an effective retention of 1.2 μm; filters were oven dried at 100 °C and residual sediment was weighed. Suspended sediment (SS), the mineral portion of the sample, was weighed after the TSS sample was burned at 550 °C for approximately 2 hours (Sidle and Campbell, 1985). Precipitation was also monitored every 10 minutes using a tipping bucket rain gauge at an open-canopy area near the LS 1 channel (Figure 5.1). Daily precipitation was collected at Hollis from 1947 to 1994, although data are missing from 1951 to 52 and from 1963 to 87.

5.4. Results and discussions

5.4.1. Occurrence and distribution of mass movement

Both the occurrence and spatial distribution of mass movement processes are important for sediment transport in headwater streams and their downstream linkages. Most of the scour and deposition related to mass movement was distributed in the logged area compared to unlogged area of Maybeso watershed after timber harvesting (Figure 5.2). Despite the absence of canopy cover in the logged area, there was little evidence of mass movement in most of the headwater channels in 1959. There were only 14 number of unvegetated slope areas detected on air photo (Figure 5.2). It is possible that logging residue and understory vegetation may have covered certain stream reaches obscuring small mass-movements. Following the storm events in 1961, scour and deposition from landslides (number of unvegetated slope areas = 30) and subsequent debris flows were clearly visible in the 1962 photographs. Multiple landslides and large depositional areas along channels were observed in deeply incised (> 15 m) landforms (Figure 5.2). Single landslides and subsequent debris flows were found in headwater systems with shallowly incised (< 15 m) landforms.

Scour and deposition from landslides (number of unvegetated slope areas: 38) and debris flows observed in the 1980 photographs and were associated with a 1979-storm event (Figure 5.2). Because riparian vegetation existed along the lower reaches of headwater streams, the travel distances of debris flows in 1979 were shorter than for the events in 1961 (Figure 5.2). This shorter travel distance may also relate to roughness contributed by young riparian trees and the higher content of woody debris in the debris flow materials in 1979 due to logging residue and the second-growth forest inputs (Johnson et al., 2000). Of the three mass erosion episodes covered in this study, the 1993 event produced the smallest number of landslides (number of unvegetated slope areas: 18) and debris flows, as observed in the 1996 small-scale photographs. Despite the frequent mass movement after timber harvesting, no landslides and debris flows directly reached the main stem of Maybeso Creek (Figure 5.2).

Sizes of storm events are significantly related to the occurrence of mass movement (Dhakal and Sidle, *in press*). Landslides in southeast Alaska typically occur during the autumn storm season from September to December (Swanston, 1967; Sidle, 1984; Johnson et al., 2000). The amount of 24-hour precipitation on October 14, 1961, and October 27, 1993, were 128.4 and 116.7 mm, respectively; the third and fifth highest values of an incomplete 20-yr record. Because average soil depth was 0.96 m in hillslopes and zero-order basins, soil within drainage depressions (i.e., zero-order basins) was believed to be fully or nearly saturated during the 1961 and 1993 storms based on the relationship between piezometric head and 24-hour precipitation in Maybeso Experimental Forest (Swanston, 1967). The relationship between rainfall return period (T_r) and 24-hour precipitation (P) was estimated from precipitation data at Hollis using the Weibull plotting position formula;

$$P = 108.7 \log (T_r) + 65.6 \quad (R^2 = 0.87; p < 0.001) \qquad [1]$$

The return intervals for the 1961 and 1993 storm events were calculated as 7.00 and 4.20 years, respectively. This finding agrees with the landslide-triggering storm estimates (5 to 8 yr recurrence interval based on 24-hour precipitation) noted by Swanston (1970) for this area. Montgomery et al. (2000) also found that a 24-hour rainfall event with a recurrence interval > 4 yr might initiate shallow landslides in the decade after logging in Oregon and Washington. Storms with recurrence intervals > 2 yr were sufficient to initiate landslides in Queen Charlotte Islands, British Columbia (Schwab, 1998). More importantly, however, combinations among slope gradient, antecedent moisture, and precipitation intensity govern the initiation of landslides (Sidle, 1984; Dhakal and Sidle, *in press*).

Changes in geomorphic and hydrologic conditions due to timber harvesting and logging roads can modify slope stability. Because the soils in the Maybeso watershed are essentially cohesionless, roots anchor the soil to bedrock and provide a long-filament binder to soil substrate (Swanston, 1970). Therefore, decreasing root strength in the period of 3 to 15 year after logging (Sidle et al., 1985) significantly affected the stability of slopes in the 1961 event. Although the two highest 24-hour precipitation amounts in Maybeso were recorded during and immediately after logging [December 31, 1953 (264 mm) and December 7, 1959 (178.2 mm)], effects of such storm events did not trigger mass movements based on aerial photo interpretation because anchoring and reinforcing effects of roots are likely still contributing substantially to stability of hillslopes. Because most of the landslides occurred just below mid-slope logging roads in 1961, unstable road-fill material may have also contributed to landslide initiation (Schwab, 1998; Wemple et al., 2001).

5.4.2. Scour, run-out, and deposition of mass movement

Channel gradient and valley configuration are important determinants of the location of scour, run-out, and deposition of mass movement. Following landslide initiation, sediment and woody debris moved as channelized debris flows toward the valley bottom of Maybeso Creek. Distances of scour and run-out zones in the LS and YA channels ranged from 275 to 700 m (Table 5.2). Within the scour and run-out zones, bedrock was exposed in 27 to 60% of the channel length (Table 5.1). Landslides initiated on hillslopes with gradients ranging from 36° to 58°. Swanston (1970) noted that landslides commonly occurred on hillslopes at or near 37 ° in the Maybeso watershed. The sediment deposition zone occurred near the foot of the slope, where channel gradient was in the range of 4.9 to 7.5° (Table 5.2). Depositional volume (sediment and woody debris transported by mass movement) was greater in LS sites (750 to 1871 m^3) than in YA channels (309 to 869 m^3) (Table 5.2). Because landslides and debris flows in LS2 and LS3 had longer scour and runout distances and initiated in second-growth conifer forests, deposited materials contained greater amounts of sediment and woody debris. In LS1 and YA3 channels, two landslides transported relatively large amounts of sediment and woody debris compared to YA1 and YA2.

Valley configuration sets the template for sediment transport and deposition. Debris flow materials were typically deposited at the bottom of the U-shaped glacial valley because of abrupt changes in landforms (Figure 5.3A). The decreased gradient reduced the momentum of debris flows. Wider valleys result in spreading and thinning of debris flows and increasing resistance to flow (Nakamura, 1986; Benda and Cundy, 1990). Separation of water and sediment due to percolation into alluvium may also reduce the momentum of debris flows. Such changes cased the formation of debris fans and log jams in the bottom of valley. Debris flows encountered standing trees and an old logging road at the foot of the hillslopes, both of which reduced the momentum (Figure 5.3B and 5.4). Roberts and Church (1986) noted the amount of sediment transported from the hillslope to main channels due to debris flows depends upon the presence or absence of a valley flat in Queen Charlotte Islands. The initial energy of landslides and debris flows partly determines the distance of sediment and woody transport. Because the landslide in LS3 was initiated at a higher altitude, the resultant debris flow they may have a greater terminal velocity and would be transported farther (Table 5.2). In contrast, debris flow material may deposit in relatively steeper gradient reaches of YA channels compared to the LS channels because landslides initiated at lower elevations in YA channels. No debris flows directly entered the main channel of Maybeso Creek due to wide and flat valley floor despite the frequent mass movements in headwaters (Figure 5.2).

Because streams were not entrenched and moved frequently on debris fans, several unsorted sediment deposits were observed at the foot of hillslopes (Figure 5.4 and 5.5). Due to sediment and woody debris deposition in 1961, 1979, and 1993, debris fans formed in the transition zone from hillslopes to floodplains (on the logging road in Figures 5.4 and 5.5). Larger sediment deposits and log jams formed 200 m downstream of the logging road in the LS3 channel. Channels shifted dramatically due to the formation of debris fans and log jams (Hogan et al. 1998). Small fans and bars were also found along channels and on terraces about 200 m downstream of the logging road in LS1 (Figure 5.4) and YA3 channels (Figure 5). Larger sediment deposits behind in-channel obstructions, such as woody debris and boulders, were also found about 200 m downstream of the reference point (logging road) in LS1 and YA3. Because channels in LS2, and YA1 eventually merged into the LS1 channel, sediment from LS2 and YA1 was transported to the downstream reaches of LS1. The volume of each deposits along and within channels ranged from 1 to 10 m^3. Such small deposits along channels as well as behind obstructions in downstream reaches may have been formed by sediment transported as flood surges and bedload movement during the 1993 event or subsequent storms (Figure 5.4 and 5.5). Due to such sediment movement, fan shaped depositions were formed along lower reaches of the headwaters. Sequential sediment movement also partially damaged riparian stands and caused local aggradation and side channel formation in downstream reaches.

5.4.3. In-channel storage of sediment

Sediment produced during and after mass movement was stored in channels. Total sediment stored behind large woody debris (LWD), fine woody debris (FWD) and other obstructions (boulders and bedrock pockets) in stream channels ranged from 0.2 to 10.1 m^3 per 100 m (Table 5.2; Figure 5.3C). Sediment stored in upper sections of the LS and YA channels was either the residual from earlier mass movement or was transported from hillslopes after recent mass movement. Sediment stored in lower sections of LS and YA channels was transported during the mass movements and subsequent events. Larger volumes of sediment were found in the lower sections of the LS channels compared to other sections. Sheet erosion, rain splash, and creep within landslide scour zones of weathered till govern sediment supply from hillslopes to LS channels. Soil erosion pedestals developed on bank slopes. Bare soil and till were affected by frost-heaving during winter and, thus, produced much coarser sediment that was temporarily stored in channels. Eroded material on hillslopes was directly transported to streams. In contrast, evidence of surface erosion and direct connections of sediment transport from hillslopes to streams existed in the YA channels due to vegetation and litter cover. Alder roots penetrated into bedrock and till and expanded on exposed substrate, thus binding soil and organic matter.

Different histories of mass movement relate to different vegetation recovery processes and in-stream sediment storage in LS and YA channels. The volume of woody debris and in-stream function of woody debris characterized the differences between the LS and YA channels (Table 5.2 and Figure 5.6). Because both branches and leaf litters were recruited from regenerating riparian alder stands, the amount of large (LWD) and fine woody debris (FWD) increased in YA channels 40 years after mass movement. The volumes of in-channel woody debris in YA channels (0.7 to 1.3 m^3/100m) were greater than in LS channels (0.2 to 0.5 m^3/100m) (Figure 5.6). Sediment storage ratio, which was calculated as the total volume of sediment divided by sediment stored behind woody debris, was significantly higher in YA (0.55) channels compared to in LS (0.22) (Gomi et al., 2001). Therefore, increases in woody debris pieces recruited from alder stands created channel roughness and turbulence and thus contribute to sediment storage (Gomi et al., 2001). Such sediment storage due to channel obstructions may be an important source for more regular sediment transport processes such as bedload and suspended sediment (Roberts and Church, 1986). Because of woody debris recruitment and in-channel storage of sediment, the percentages of exposed bedrock slightly was slightly lower in the YA channels (Table 5.1). For much longer periods (> 50 years), woody debris inputs and colluvial material are stored in hollows and channels until landslides and debris flows remobilize the material. Larger sizes of materials are likely stored in the channels because of the limited transport capacity in small streams.

5.5. Transport of bedload and suspended sediment

Bedload and suspended sediment transport in streams is linked to sediment supply from hillslopes and in-stream storage. Rain splash and sheet erosion on glacier tills and forest soils produce mostly finer sediment, such as clay, silt, and fine sand, most of which is transported as suspended sediment. Small bank and slope failures typically produce coarser sediment and alter channel morphology. During the October 21, 1999 storm, a small bank failure occurred in LS1, 30 m upstream from the weir. According to the equation [1], the return interval of the 24-hour precipitation (71 mm) was 1.5 years. Based on Swanston's (1967) equation, 71 mm of rainfall in 24-hour precipitation would cause a 0.65 m rise in piezometric head. Thus, sections of shallow soil near the channel bank may have been nearly saturated during this storm. Nevertheless, bank and slope undercutting due to higher discharge may have played an important role in creating unstable conditions in the side-slopes. The small bank failure produced 1 to 1.5 m^3 of sediment, including soil and weathered till, based on dimensional estimates. Failed material consisted of weathered till (clay and silt) and coarse fragments (gravels and cobbles). Since the capacity of the weir pond in LS1 was less than 1 m^3, a maximum 85-90% of the sediment was captured behind the weir. Because of the sudden supply of saturated sediment from the bank failure during the high discharge, the sediment was probably mobilized and transported downstream during the storm. Such a channelized mass wasting process with a large sediment flux and higher water content is described as a hyperconcentrated flow.

Sediment produced from hillslopes and stored in channels is subsequently transported downstreams as bedload and suspended sediment depending on the size of storm events, sediment supply, and channel roughness. The relationships between sediment deposition at weir ponds in LS1 and YA1 and maximum 24-hour rainfall during the various sampling intervals from September 1 to November 15, 1999 are shown in Figure 5.7. Bedload sediment transport in LS1 was 2 to 10-hold greater than in YA1. Significant exponential relationships were derived between the maximum 24-hour precipitation (P: mm) and the total volume of sediment (V: m^3) in LS1 and in YA1 (Figure 5.7).

$$\text{LS1: } V = 7.8 \times 10^{-4}\, e^{0.104P} \quad (R^2 = 0.90,\ P < 0.001) \qquad [2]$$

$$\text{YA1: } V = 7.4 \times 10^{-4}\, e^{0.056P} \quad (R^2 = 0.66,\ P = 0.008) \qquad [3]$$

The exponent in equation [2] (LS 1) is significantly different compared to equation [3] (YA1) ($F = 5.71$, $p = 0.03$) at the $\alpha = 0.05$ confidence level, while the constants are similar. For small rainfall events (e.g., 10 mm in 24-hour), bedload movement was similar in both channels. During larger events, total bedload movement in the LS1 was significantly larger than in YA1. In addition, the relationship between maximum 24-hour precipitation and volume of sediment in LS1 was stronger ($R^2 = 0.90$) compared to YA1 ($R^2 = 0.66$) (Figure 5.7). These findings imply that bedload sediment response to rainfall input in LS1 was less complex that in YA1. This result may relate to the higher availability of sediment in the LS1 channel due to its constant supply from unvegetated bank slopes. Variations in bedload transport in YA1 during storms may be caused by sediment storage behind woody debris and boulders or the sudden release of sediment from such storage sites (Adenlof and Wohl, 1994). Median diameter (D_{50}) of bed load was approximately 10 mm and was smaller than channel bed substrate (Table 5.1). Although there was no replication of LS1 and YA1, we assumed that similar relations between bedload transport and rainfall might be observed in the other LS and YA channels.

Total sediment yield during the selected storm events was estimated from bedload and suspend sediment yield, although we could not collected suspended sediment samples during all phases of storm events. Total suspended sediment yield from LS1 (19 to 207 kg per event) was 10 to 20-fold greater than from the YA1 (2 to 37 kg per event). Suspended sediment accounted for a smaller percentage to the total sediment yield in YA1 (26, 32, and 68%) compared to LS1 (49, 67, and 70%) during the storm events on September 8 and 22 and November 1, respectively. Because less bedload was transported late in the storm season, suspended sediment comprised 68% of the total sediment yield in YA1 during November 1 storm. Lenzi and Marchi (2000) estimated that suspended sediment contributed from 16 to 100% of the total sediment yield in a small stream in Italy. These large variations in the percentage of suspended sediment are affected by sediment sources, the relative amount of bedload, seasonal changes in availability of sediment, and the instantaneous supply from the slope and the channel bed (Sidle and Campbell, 1985; Lenzi and Marchi, 2000). Cumulative bedload yield during the 1999 monitoring period was 2.0 and 0.1 m^3 in LS1 and YA1 channels, respectively. Therefore, assuming an average proportion of suspended sediment to total sediment of 62% in LS1 and 42 % in YA1 throughout the storm season, total sediment yields in LS1 and YA1 channels were approximately 5.3 and 0.2 m^3, respectively.

5.6. Sediment transport and hydrogeomorphic linkages

5.6.1. Temporal variation

Based on results of sediment transport and storage in the LS and YA channels of Maybeso watershed, temporal variation in sediment transport occurs along with changes in linkages from hillslopes to streams. These changes are related to mass movement and vegetation recovery processes. Ground vegetation cover on previously exposed soil and till, and the regeneration of alder stands in the riparian areas after mass movements, modifies soil erosion processes and linkages from hillslopes to streams (Shimokawa, 1984). After the regeneration of alder riparian stands, the nitrogen-supplemented soils may improve hydrological conditions and facilitie regeneration of other successional plants (Bormann and Sidle 1990). Soil under alder riparian stands may be improved with the accumulation of organic matter, increases in flora and fauna (possibly contributing to the formation of macropores), development of soil structure, and increases in infiltration capacity and hydraulic conductivity (Bormann and Sidle 1990). The decoupling of side-slopes and streams gradually occurs as slopes revegetate and consequently decrease the supply of sediment from hillslopes to channels in YA.

The role of woody debris related to the transport and storage of sediment may change with the succession of riparian stands after mass movement. Woody debris recruitment may change from early establishment of alder to the replacement with alder to conifers in later stages of succession. Succession patterns of riparian forests after timber harvesting differ with and without mass movement in headwater streams (Gomi et al., 2000). Likens and Bilby (1982) noted that the succession of riparian stands after logging modified the amount of woody debris dams for a periods of 50 to 100 years after disturbances. Although woody debris recruited from alder riparian stands contributed to sediment storage 40 years after mass movement, alder typically decomposes and fragments more rapidly compared to conifers (Harmon et al., 1986).

Dominant sediment transport modes after timber harvesting in headwater streams of the Maybeso watershed can be grouped in relation to triggering storm events (Table 5.3). Landslide and debris flows after timber harvesting were triggered by storm events with recurrence internals ≥ 5 years. Relatively unsorted materials (≥ 100 m^3) including cobbles and boulders ($D_{50} \geq 200$ mm) and large woody debris pieces were transported during these events. Hyperconcentrated flows may occur when large amounts of sediment are transported from the hillslope and accumulate in channels (Table 5.3). Although only one case was observed, approximately 1 m^3 of sediment from a slope failure was transported as a hyperconcentrated flow during a storm with a recurrence interval of 1.5 to 5 yr. A flood surge may also occur if a log jam breaks (Nakamura et al., 2000). Gravels, cobbles, and small boulders ($10 < D_{50} < 200$ mm) and fine woody debris pieces were transported during such intermediate events (Table 5.3). Sediment ≤ 1 m^3 was transported more regularly (daily rainfall return period ≤ 1.5 yr) as bedload and suspended sediment (Table 5.3). Because such materials were smaller than channel bed substrate, bedload materials were more selectively transported during storm events (Adenlof and Wohl, 1994). Materials smaller than gravel as well as organic matter (e.g., leaves and branches) were typically transported during these smaller events.

5.6.2. Spatial variation

A shift in the dominant geomorphic processes from up to downstream reaches within headwater streams causes various types of deposition and erosion features along channels. Sequential changes from colluvial (mass movement) to alluvial-dominated (bedload and suspended sediment) processes occurred within 1 km in the Maybeso watershed due to changes in channel gradient, material size, and valley configuration. Such changes also modified riparian structure and channel form (Nakamura et al., 2000). Most of the sediment produced by the mass movement formed debris fans at the bottom of the U-shaped glacial valley. A portion of this deposited material was subsequently transported as flood surges, bedload, and suspended sediment due to break up of log jams, bank erosion, and channel avulsions on the debris fans, while most of deposited sediment remained in the same location for longer periods. For instance, residence time of deposited materials on the bottom of valleys may be much longer than 10^4 years (Dietrich and Dunne, 1978). Sediment stored in channels mobilizes more frequently depending on the stability of obstructions. Bedload sediment may gradually be transported from downstream reaches of debris fans to the main stem of Maybeso Creek. Suspended sediment is transported directly to the main stream of Maybeso Creek during storm events. The dominant channel reach morphology changes from bedrock and cascade to step-pool and pool-riffle in headwater streams (Montgomery and Buffington, 1997). Sediment movement related to mass wasting and the recovery process alters the distribution of such channel reach types.

Although tight linkages from hillslopes to streams within headwater streams were observed, routing processes from the downstream portion of headwaters to the main channel of Maybeso Creek were not strongly coupled (Figure 5.8). Because of decreases in the channel gradient and increased valley width, sediment movement is more dispersed in downstream reaches. Unit stream power is lower in wider and shallower channels and this induces sediment deposition. Stream water percolates into substrate in some reaches and, conversely, groundwater recharges through the streambed. Wide floodplains, beaver ponds, and bogs intercept and dissipate material transport from headwaters to downstream reaches (Figure 5.8). Bryant (1980) documented channel changes in Maybeso Creek before and after timber harvesting and found that log jam formation, bank instability, and sediment accumulation occurred after logging. Because mass movements did not directly enter the main channel (Figure 5.8), most of sediment in Maybeso Creek was likely the result of bedload transported from tributaries, bank erosion, and side channel formation in floodplain materials. Schwab (1998) estimated that a greater amount of sediment was transported by mass movement in the early 1900's compared to after timber harvesting in the 1950's in Queen Charlotte Islands. Hogan et al. (1998) estimated that the most log jams were formed during and after mass movement. Slaymaker (2000) also noted the different findings in the occurrence of mass movement and log jam formations of these studies. Such results may be related to linkages of sediment and woody debris movement between headwater streams and downstream systems at various spatial and temporal scales (Hogan et al., 1998) (Figure 5.8).

5.7. Summary and Conclusions

Hydrological processes with varying magnitudes and frequencies alter sediment movement after timber harvesting in headwater systems of Maybeso watershed. The history of mass movement controls the availability of sediment in channels and the structure of riparian vegetation. Recovery of vegetation after episodic mass movement modifies bedload and suspended sediment transport and in-channel storage of sediment in headwater streams. The dynamics of sediment movement in managed forest headwaters can be summarized according to the following sequence: (1) mass movement after timber harvesting is triggered by storm events with recurrence intervals > 5 yr in logged areas; (2) sediment and woody debris redistributes from upper to lower reaches of channels; however, debris flows do not enter main channels; (3) subsequent sediment movement is transported from debris fans formed at the bottom of the U-shaped glacial valley; (4) greater amount of bedload and suspended sediment was transported immediately after mass movement; (5) amount of bedload and suspended sediment transport largely depends on vegetation recovery processes and amount of woody debris recruitment after mass movements; and finally (6) the sequence of sediment transport and transformation of sediment movement modes from headwaters to downstream reaches alter riparian stands and channel morphology: this in turn creates heterogeneous riparian and in-stream landscapes in Maybeso watershed.

Landforms strongly influence sediment transport with respect to hydrologic and geomorphic linkages from hillslopes to streams and from headwaters to downstream reaches in Maybeso watershed. Landform characteristics such as valley incision, valley floor topography, and vegetation cover control the spatial and temporal distribution of sediment transport and storage (Nakamura et al., 1995; Benda and Dunne, 1997b). Such landform characteristics are also important for understanding the patterns of disturbances in riparian zones and channel morphology throughout the channel network (Nakamura et al., 2000). Therefore, hydrogeomorphic linkages in different landforms must be evaluated to understand the dynamics of water, sediment, nutrients, and organic matter in channel networks and riparian zones.

Knowledge of sediment transport and storage and the interaction of sediment movement with riparian vegetation and woody debris may aid in the understanding of dynamic material fluxes and processing in headwater streams. Since the total area of headwater systems comprises a major portion of the channel network, material transport in headwater systems is critical to understanding the dynamics of channel networks (Benda and Dunne, 1997a; Sidle, 2000). In particular, the importance of headwater streams for the habitat and food supply of stream biota are a major concern in forest management.

Table 5.1 Characteristics of the study sites

	Landslides and Debris flows	Drainage area (Km^2)	Length of studied channel (m)	Mean channel gradient (%)	Mean bankfull width (m)	Exposed bedrock (% Length)	D_{50} (mm)	Number of LWD per 100m		Number of FWD per 100m
								Total	In-channel	
LS1 Upper	1993/1979	0.21	340	40.3 (11.0)	1.2 (0.6)	26.7	30	15	4	15
LS1 Lower			400	9.9 (5.8)	2.6 (1.5)	0.0	25	40	29	106
LS2 Upper	1993	0.27	150	31.0 (12.3)	1.6 (0.4)	40.7	31	37	27	67
LS2 Lower			250	13.7 (6.0)	1.8 (0.6)	0.0	30	54	45	71
LS3 Upper	1993	0.35	300	31.7 (11.5)	2.8 (1.3)	59.8	43	57	27	53
LS3 Lower			350	9.8 (8.1)	3.7 (1.3)	0.0	29	80	46	116
YA1 Upper	1961	0.22	125	36.6 (9.3)	1.1 (0.5)	26.0	36	24	21	41
YA1Lower			100	17.5 (6.8)	1.4 (0.5)	2.0	35	52	37	81
YA2Upper	1961	0.14	225	42.7 (9.1)	0.9 (0.3)	38.0	40	20	16	55
YA2 Lower			125	18.6 (7.1)	0.9 (0.3)	0.0	27	14	14	48
YA3 Upper	1979/1961	0.21	150	28.9 (11.2)	2.0 (0.6)	47.1	38	29	23	27
YA3 Lower			300	17.4 (7.3)	1.9 (0.6)	0.0	28	66	59	105

Note: LS, recent landslide (logged from 1953 to 1957 and landslide and debris flows in 1979 and (or) 1993); YA, young alder riparian forest (logged from 1953 to 1957 and landslides and debris flows in 1961 and (or) 1979).
Standard deviations are expressed in parentheses.
Sites are divided into scour/run-out (upper section) and deposition (lower section) zones of landslides/debris flows.

Table 5.2 Sediment transport during mass movement and in-channel storages of sediment.

	Sediment transport during landslides and debris flows						In-channel storage of sediment (m^3 per 100m)		
	Source and run-out zones			Deposition zones					
Site	Initiation area	Distance (m)	Hillslope gradient [a] (degree)	Total volume of sediment (m^3)	Channel gradient [b] (degree)	Distance to terminus of deposition (m)	LWD	FWD	Others
LS1 upper	Road fill	350	47				0.4	0.2	2.5
LS1 lower				750	5	100	2.8	1.6	10.1
LS2 upper	Second growth forest	600	43				1.1	0.9	2.6
LS2 lower				1045	5	85	3.3	0.9	3.8
LS3 upper	Second growth forest	700	55				2.3	0.5	4.7
LS3 lower				1871	5	300	4.1	0.2	9.6
YA1 upper	Road fill	330	52				1.9	1.3	3.7
YA1 lower				309	8	150	7.9	0.8	0.6
YA2 upper	Below road	275	36				0.8	1.2	2.0
YA2 lower				440	9	85	4.5	0.2	7.8
YA3 upper	Road fill	350	50				1.7	0.7	1.9
YA3 lower				869	6	230	4.1	0.4	3.4

Note: see Table 1 for stream type codes.
a) Hillslope gradient was measured near the initiation of landslide.
b) Channel gradient measured at the beginning of deposition zones.

Table 5.3 Mode of sediment movements in headwater streams in the Maybeso watershed.

	Return periods in 24-hour precipitation	Total sediment volume	Mobile material	Geomorphic changes
Landslides and debris flows	≥ 5 years	≥ 100 m^3	D_{50} > 200mm Large woody debris	Fans and new channels form Channel aggradation Channel reach types rearranged
Hyperconcentrated flow Flood surge	1.5 to 5 years	1 – 100m^3	10 < D_{50} < 200mm Fine woody debris	Small fans, lobes, side channels form Minor steps collapse Local aggradation
Bedload and suspended movement	≤ 1.5 years	≤ 1 m^3	D_{50} = 10 mm Leaves and branches	Moderate channel erosion and deposition Local changes in pool depth

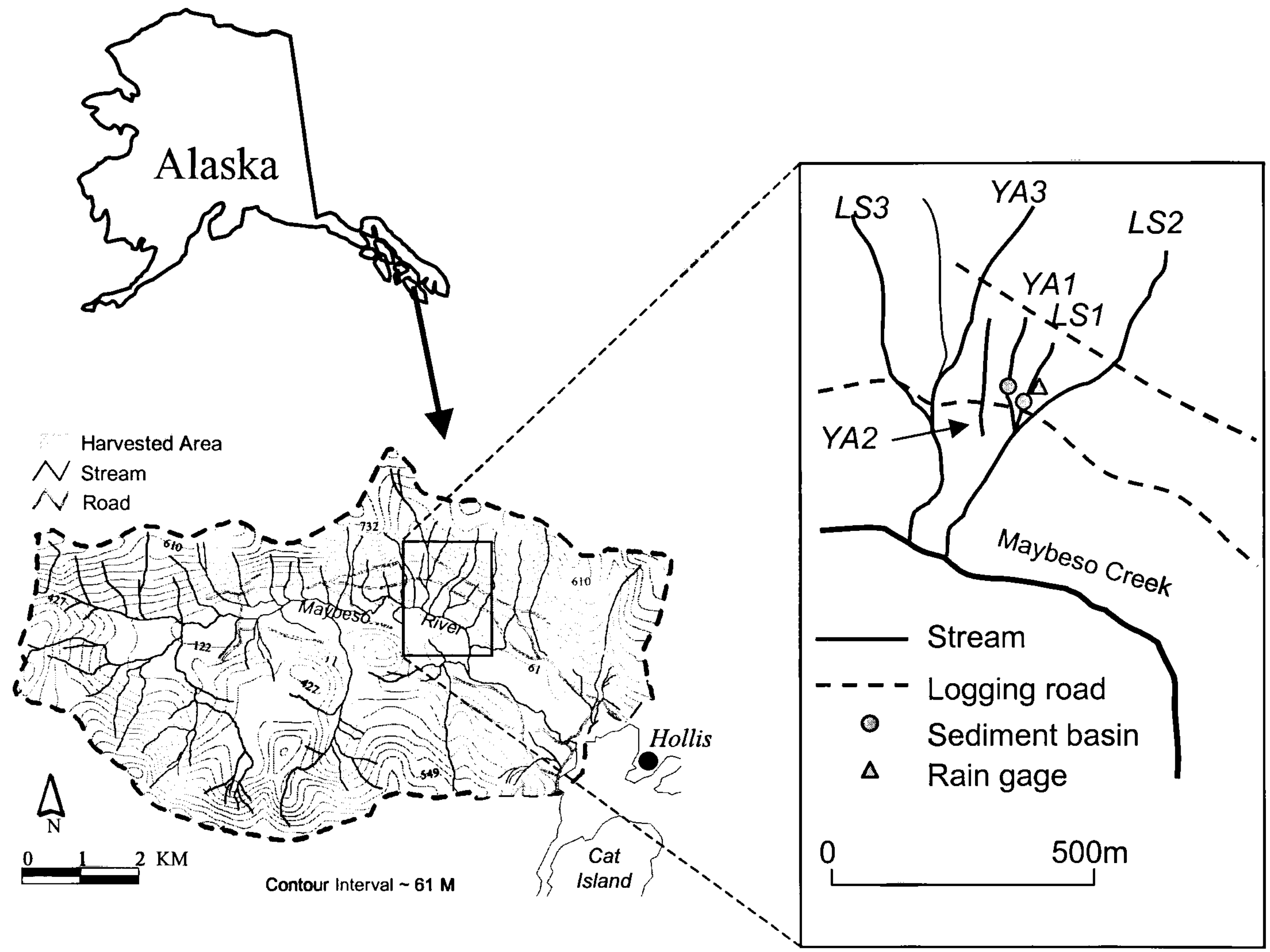


Figure 5.1 Study sites in Maybeso valley, southeast Alaska: weirs were located in LS 1 and YA 1 channels to capture bedload sediment. A tipping bucket rain gauge was located near LS 1 and the long-term weather station is located in Hollis. Broken line shows watershed boundary. See Table 1 for definition of the stream types.

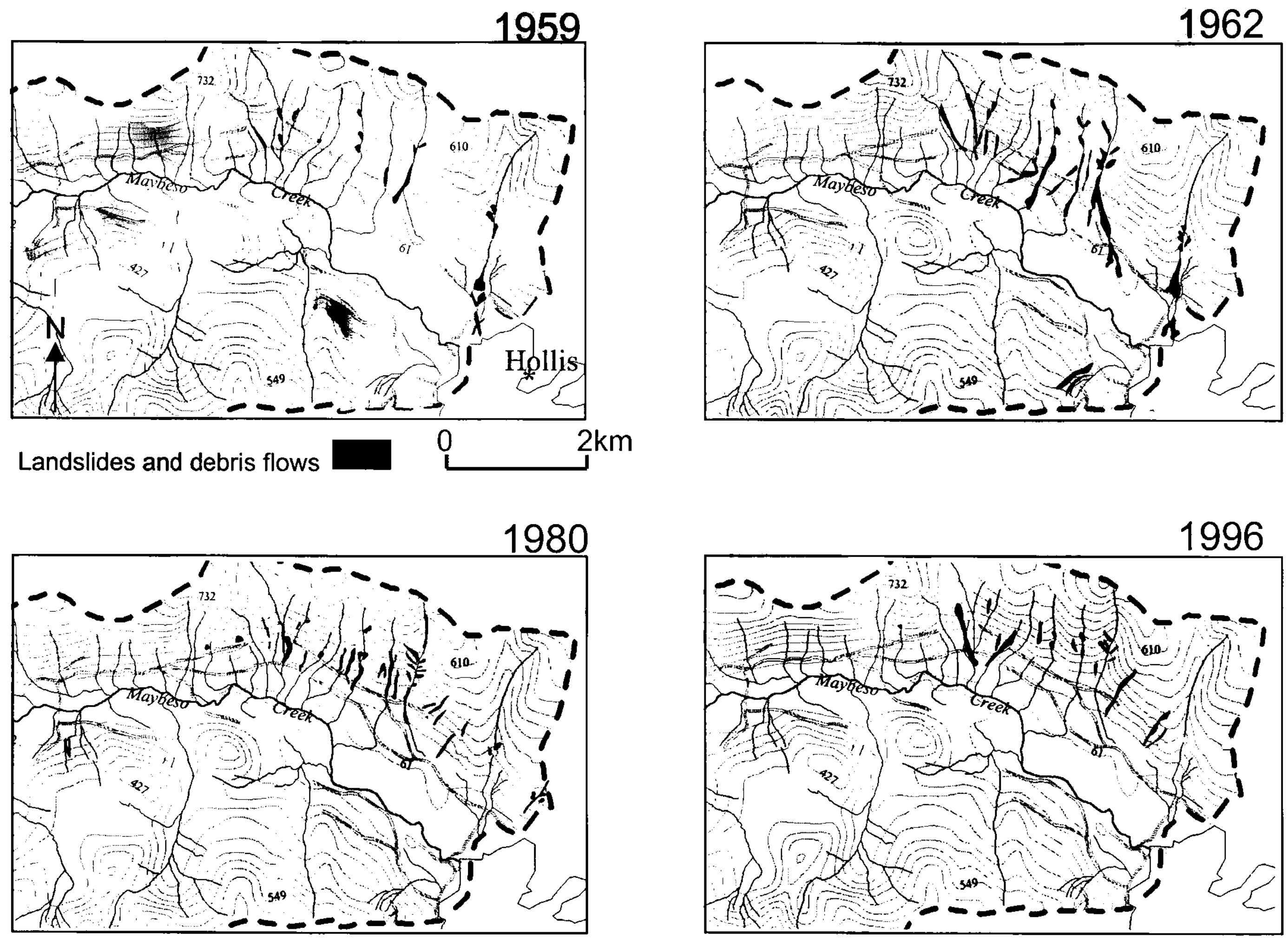


Figure 5.2 Distribution of landslides and debris flows after timber harvesting in the Maybeso watershed. Spatial distribution of mass movement was estimated from aerial photographs. Timber harvesting was conducted in 1953 and 1957. Most of the scour and deposition due to mass movement was observed within the logged area.

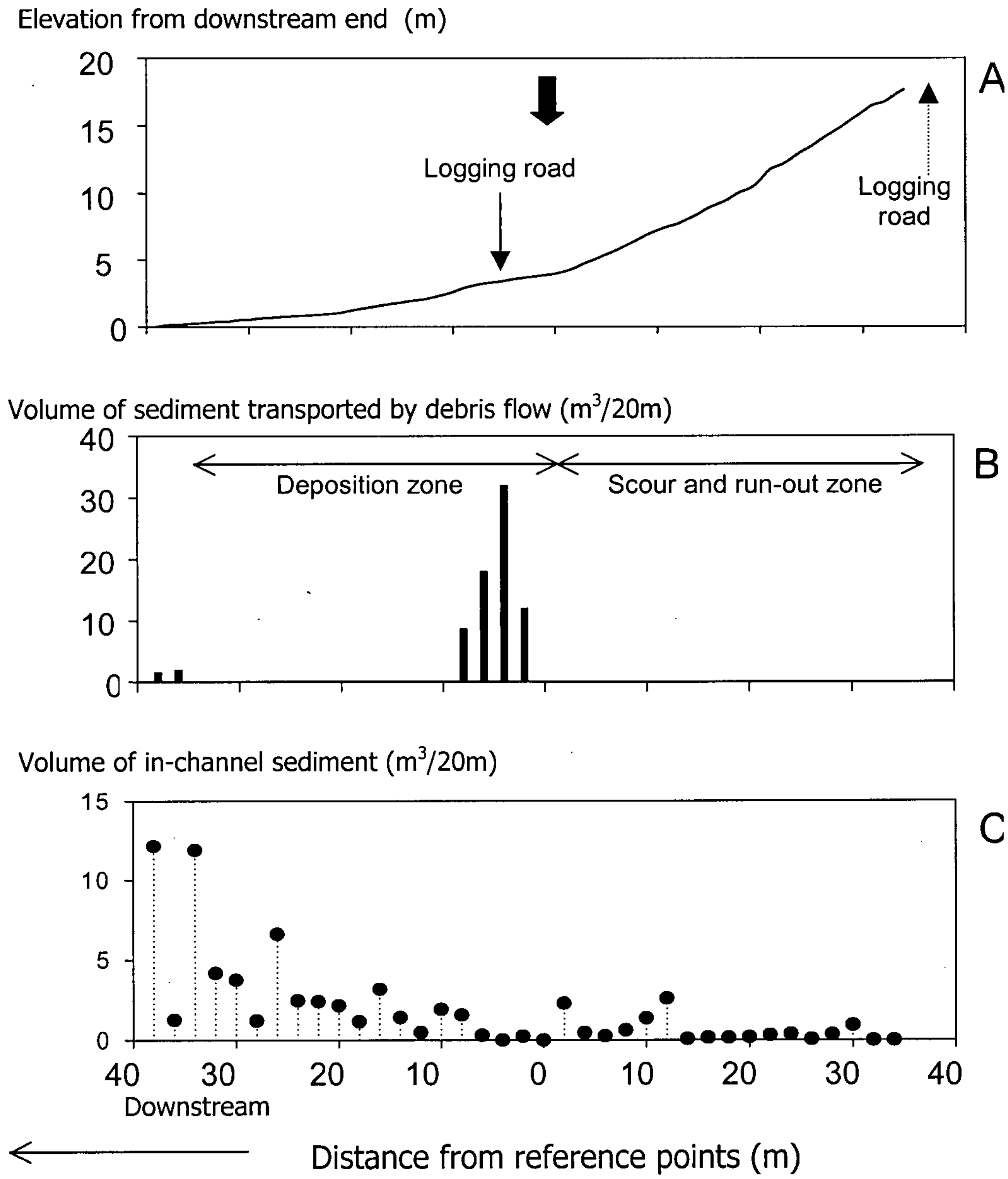
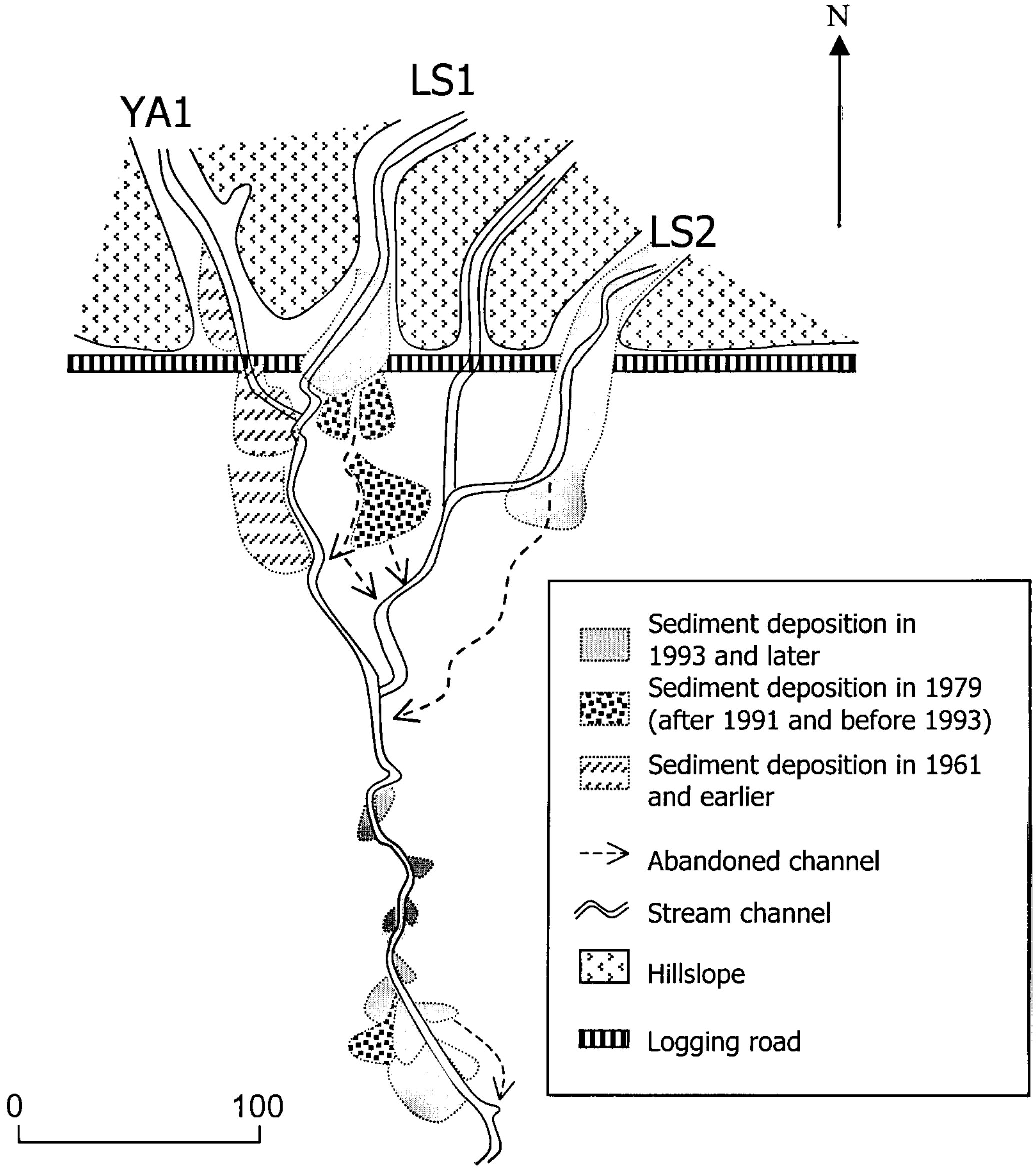
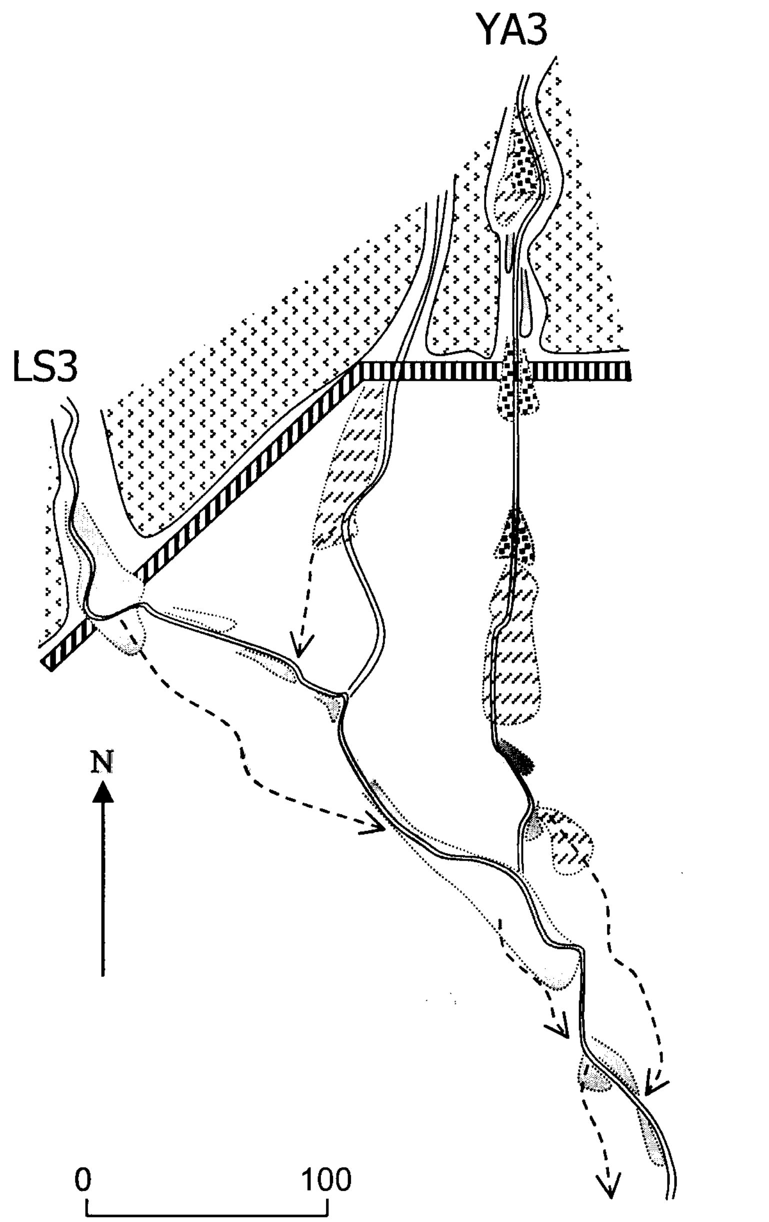


Figure 5.3 Longitudinal profile, distribution of in-channel sediment, and sediment due to debris flows along LS 1. Small arrows show old logging roads located at the foot (solid arrow) and middle (dotted arrow) of hillslopes; large arrow shows the reference point (0 m) for the stream survey. Volume of sediment transported and deposited due to mass movement is estimated in Figure 3B. Volume of sediment stored behind woody debris and the other channel obstructions (e.g., boulders) is described in Figure 3C.



Volumes of sediment	1961	1979	1993	Downstream
LS1	-	548	160	> 42
LS2	-	-	1045	
YA1	309	-	-	

Figure 5.4 Sediment deposition due to debris flows and subsequent sediment movement in the LS1, LS2, and YA1 channels. Debris fans formed at the bottom of the glaciated valley near the logging road. The table shows the volume of mobile sediment in different years estimated in the field.



Volumes of sediment	1961	1979	1993	Downstream
LS3	-	-	1871	> 20
YA1	501	249	119	

Figure 5.5 Sediment deposition due to debris flows and subsequent sediment movement in the LS3 and YA3 channels. More sediment deposits due to debris flows in LS3 were found approximately 200 m downstream of logging roads. Sediment deposits of varying ages were found along YA3. The table shows the volume of mobile sediment in different years estimated in the field. See Figure 5-4 for the code on the map.

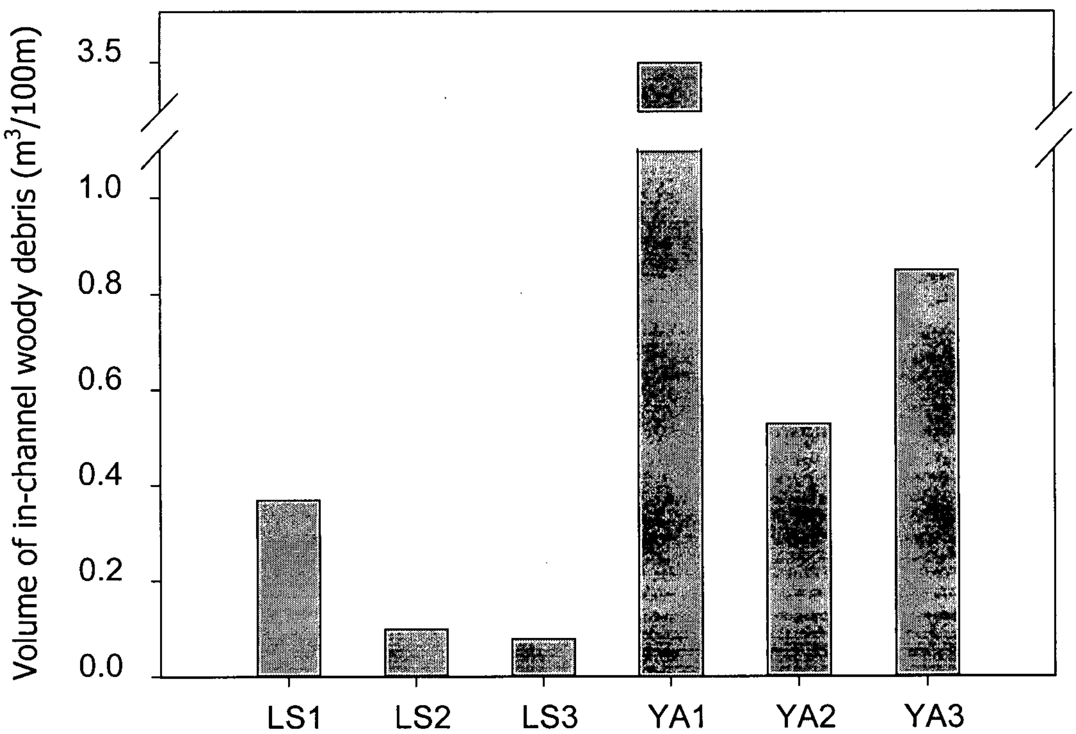


Figure 5.6 Volume of in-channel large woody debris in the upper reaches of LS and YA channels. In-channel volumes of large woody debris (LWD) in YA streams were higher than those in LS channels

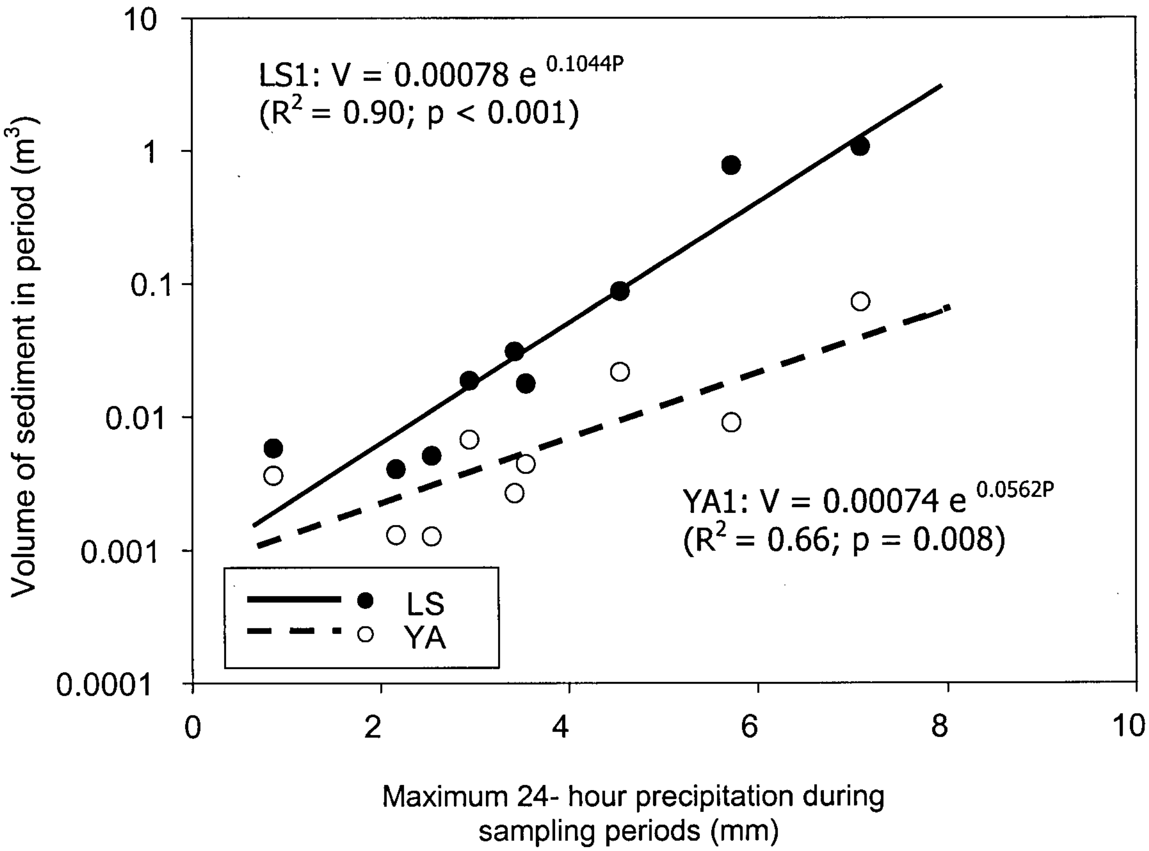


Figure 5.7 Relationships between the volumes of sediment deposited in weir ponds (V: m^3) and maximum (event) 24-hour precipitation (P: mm) for sediment sampling periods in LS 1 and YA 1 from September to November 1999.

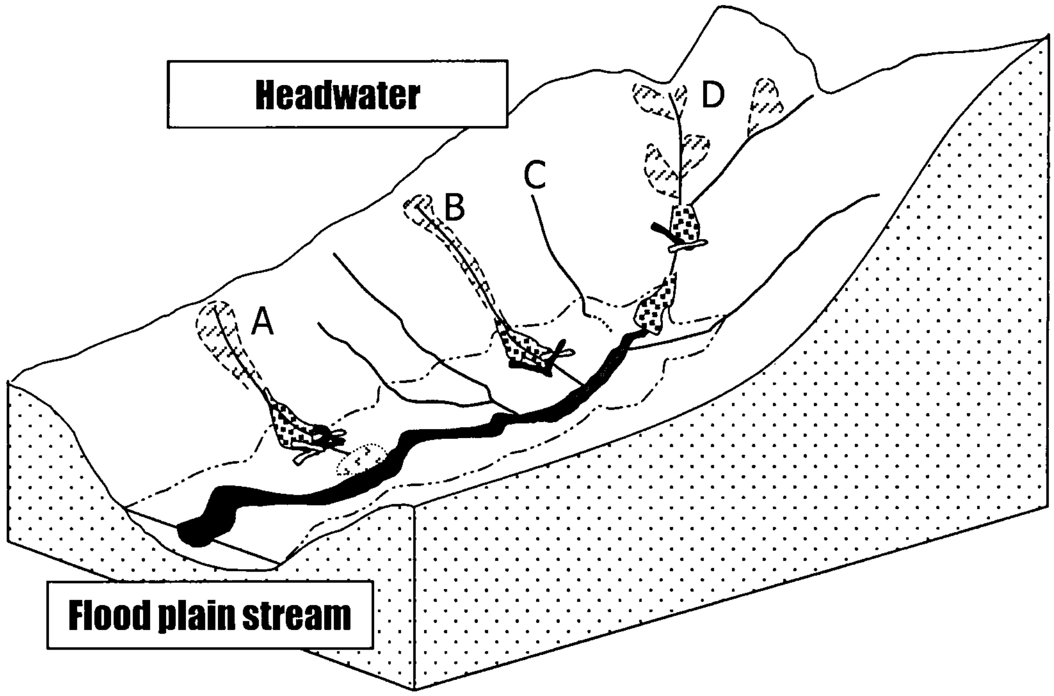


Figure 5.8 Schematic view of linkages from hillslope to channels, and from headwater streams to main channels. Multiple landslides are often found in headwater systems with ravine landforms, while single landslides affect channels with shallowly incised landforms. **Headwater A**: Headwater channel eventually merges into wetlands and beaver ponds in both shallowly incised and ravine landforms. **Headwater B**: Single landslides and channelized debris flows in headwater systems with shallowly incised landforms; sediment and water diffuse near the foot of hillslopes and do not directly enter the main channel. **Headwater C**: Because of alluvial material in the floodplain, the stream becomes influent during the dry season. **Headwater D**: Multiple landslides are found in headwater systems. Because of the larger amount of sediment, sediment is transported near or in the main channel.

Summary, synthesis and conclusion

Summary

The findings of the integrated components of this thesis show how woody debris and sediment dynamics are associated with typical forest management and disturbance regimes at different temporal and spatial scales. First of all, the uniqueness and interaction of hydrologic, geomorphic, and biological processes among hillslopes, zero-order basins, and stream channels is presented (Chapter 1). The importance of headwaters as sources of sediments, water, nutrients, and organic matter to downstream reaches was emphasized. The remainder of the thesis (Chapters 2 to 5) assesses the distribution of woody debris and sediment in headwater streams as well as the function of woody debris for storing sediment related to management and disturbance regimes. The timing of clear cutting and landslides/debris flows modified channel steps and reach morphology in headwater streams. Both woody debris and sediment supply are important for the formation of steps and the modification of reach types. In Chapter 4, it was shown that responses of bedload and suspended sediment transport during storm events were related to the availability of sediment and woody debris. The availability of sediment and woody debris greatly modified the threshold, transport processes and storage of sediment. Finally, spatial and temporal variations of sediment movement (episodic and chronic sediment movement) and their linkages from hillslopes to channels were assessed. The history of episodic sediment movement as well as recovery processes from these disturbances appears to control chronic sediment movement. The key findings of the five chapters are summarized in the following sections.

Importance of headwater streams (Chapter 1)

Headwater systems are the important sources of water, sediment, nutrients, and organic matter for downstream systems (Hack and Goodlett, 1960; Sidle, 2000). Headwater streams are defined as small (bankfull < 2 m), steep gradient (> 0.10) channels, which include hillslopes, zero-order basins (Tsukamoto et al., 1982), and first and second order channels (Strahler, 1957). Such small headwater streams are also recognized as important habitat for macroinvertebrates (Richardson, 1992) and food sources for juvenile salmonid and residential trout in Pacific Northwest (Bryant, 1984). Headwater catchments can comprise a major portion (up to 70% or more) of the total area for a larger watershed (Tsukamoto et al., 1982). Because many headwater systems are located within larger watersheds, a linear abstraction of stream ecosystems (e.g., Vannote et al., 1980) is not suitable for understanding the processes and roles of headwater streams in channel networks, which are approximated as branched structures. A paradigm shift from linear to branched systems is necessary to understand the processes and linkages of physical and biological dynamics in stream systems (Fisher, 1997). Moreover, because logging activities are typically conducted around headwater streams, establishing sound management practices for the conservation of headwater ecosystems is a central issue in Pacific Northwest.

Watersheds can be classified as headwater and network systems based on the continuous and discontinuous nature of material dynamics from hillslopes to streams and from headwaters to downstream reaches. The maximum drainage area of headwater systems is 1 km^2 based on the continuum of hydrogeomorphic processes (Woods et al., 1988; Montgomery and Foufoula-Georgiou, 1993; Swanson et al., 1998). However, the size of headwater systems may be modified by drainage density, which varies through several orders of magnitude in landscape. Processes from hillslopes to streams and from terrestrial to aquatic environments are tightly linked and continuous in headwaters, while the continuity from headwater to downstream systems varies depending on changes in channel gradient, tributary junctions, and valley width. For the downstream reaches, geomorphic processes typically change from mass movement to fluvial-dominated (Montgomery and Foufoula-Georgiou, 1993). Connectivity and distribution of headwater streams are important to evaluate the linkages between headwater and downstream systems. Because of their unique geomorphic, hydrologic, and biological processes and attributes, the dynamics of headwater streams require more intensive and extensive investigation. In particular, sediment and woody debris dynamics are the key factors in understanding the linkages from hillslopes to streams and from headwaters to downstream reaches.

Distribution and accumulation of woody debris and sediment (Chapter 2)

Accumulation and distribution of woody debris and sediment are largely related to riparian conditions, which in turn rely upon disturbance sequences, such as timber harvesting and landslides. Although various geomorphic and biological functions of woody debris have been investigated (e.g., Harmon et al., 1986), the roles of woody debris for storing sediment and modifying channel morphology in steep headwater streams are poorly understood. Large woody debris (LWD: diameter ≥ 0.1 m; length ≥ 0.5 m), fine woody debris (FWD: diameter 0.03 –0.1 m; length ≥ 0.5), fine organic debris (FOD: accumulations of leaves and branches), and sediment deposition were measured in 15 steep headwater streams with five management and disturbance regimes (LS, YA, YC, CC, and OG). Differences in the amount of woody debris pieces and sediment deposition were statistically tested using a mixed effect analysis of covariance model. Clear-cut channels, logged in 1995, contained large accumulations of logging residue that initially provided sites for sediment storage. Half of the LWD in clear-cut channels was recruited during and immediately after logging. Woody debris from logging activities remained in the young growth conifer channels 37 years after logging. Numbers of LWD in clear-cut and young conifer channels were significantly higher than in old-growth channels, although numbers of FWD pieces were not significantly different due to higher recruitment from old-growth stands. Channels that experienced recent (1979 and/or 1993; LS channels) and earlier (1961 and/or 1979; young alder riparian forest) scour and/or runout of landslides and debris flows contained less LWD and FWD, although greater volumes of LWD and FWD were found in deposition zones. The volumes of sediment stored in young alder and recent landslide channels were higher than in the other channels. The ratio of sediment stored behind woody debris to total sediment volume was greater in young alder channels compared with recent landslide channels, however, this may have been due to higher recruitment of LWD and FWD from the adjacent young alder stands. Numbers of LWD and FWD pieces in all streams were significantly correlated with the volumes of sediment stored behind woody debris, while Bilby and Ward (1989) noted that the volume of woody debris correlated to the volume of sediment. Higher numbers of LWD and FWD pieces (multiple dams) were more important for greater sediment storage in headwater streams than volumes. Woody debris and sediment accumulations also formed channel steps and altered hydraulics. Differences in geomorphic attributes also affect the amount and regimes of bedload and suspended sediment transport in headwater streams.

Channel steps and reach morphology (Chapter 3)

Channel steps, most commonly formed by boulders, are the most significant geomorphic units that affect the stability of channels in steep headwater streams. In forested channels, woody debris pieces and jams also contribute to the formation of channel steps. Because channel units such as pools and steps are the subunits of channel reaches (e.g., Grant et al., 1990), the distribution and abundance of channel steps can alter the distribution of reach types. Thus, the effect of five management and disturbance regimes on channel steps and reach morphology was examined in 16 headwater channels.

Differences in step geometry, such as height and interval length of steps, among stream types (LS, YA, YC, CC, and OG) were measured and statistically tested using mixed effect analysis of covariance. While numbers, intervals, and heights of steps did not differ, step interval length significantly differed among management and disturbance regimes. Similar to the findings by Whittaker (1987), a negative exponential relationship between channel gradient and average length of step intervals was observed in fluvial reaches (< 0.25 unit gradient) of the LS and OG channels. No such relationship was found in upper reaches (≥ 0.25 gradient) where colluvial processes dominated. Similarly, Wohl and Grodeck (1994) found no significant relationship between step interval length and gradient in steep (> 0.2) channels. Recruitment of old and recent logging slash as well as woody debris recruitment from regenerating riparian stands may obscure any strong relationship between step geometry and channel gradient in the YA, YC, and CC channels.

Changes in the number of channel steps were related to the amount of woody debris available to modify channel reach types. Channel reaches were described as pool-riffle, step-pool, step-step, cascade, rapids, and bedrock (modified from Montgomery and Buffington, 1997; Zimmerman and Church, 2001). In step-step reaches, pools do not form between steps. The geometry of channel steps such as step interval length and height characterized reach types. Fluvial processes dominated in pool-riffle and step-pool reaches, while colluvial processes dominated in bedrock reaches. Both fluvial and colluvial processes dominated in step-step, cascade, and rapids reaches. Step-step reaches appear to be a transitional channel type between cascade and step-pool reaches. Step-step reaches dominate in clear-cut channels with gradients < 0.25 because logging slash forms steps and impounds sediment. Recruitment of woody debris thus contributed to the formation of steps and then sequentially induced the modification of channel reach types from step-pools to step-steps. Scour, runout, and deposition of sediment and woody debris from landslides and debris flows modified the distribution of reach types (bedrock, cascades, and step-pools) and the structure of steps within the reaches. The differences in the distribution of channel steps and reach morphology among stream types are likely to modify bedload and suspended sediment transport.

<u>*Bedload and suspended sediment transport (Chapter 4)*</u>

The sediment dynamics of steep headwater channels may differ in many ways compared to those of low gradient channels. Woody debris pieces and related changes in geomorphic attributes (e.g., steps and pools) affect sediment transport in stream channels. The variation of bed topography may modify the variation of material exchange between what is transported and what is resident in the channel bed. Landslides and debris flows and their recovery processes alter the amount of woody debris and available sediment: this in turn affects patterns and threshold discharges for bedload and suspended sediment movement. Logging activities also modify channel morphology, hydrologic regime, and availability of sediment. Therefore, synoptic bedload and suspended sediment transport was examined in four (LS, YA, CC, and OG) of the 16 study streams (discussed in Chapters two and three) reflecting the full range of management and disturbance regimes.

The amount of bedload sediment was correlated to peak discharge and effective discharge volume in each stream. Because surface erosion and small bank failures regularly occur on unvegetated soil, the LS channel produced 15 times more sediment than the YA, CC, or OG channels. Median diameter of transported materials in all streams was smaller than that of the channel bed, although the peak discharge exceeded the threshold for bedload entrainment by 10-fold. This result thus implies selective transport occurred rather than equal mobility (Whiting et al., 1999). Sediment exhaustion occurred after bankfull peak discharge for supply-limited conditions in the YA channel. Sediment transport in the LS channel increased after the annual peak flow due to the occurrence of a small bank failure. Thus, clockwise and counterclockwise seasonal hystheresis may occur in YA and LS during supply-limited and energy-limited conditions, respectively. Bedload tracers were transported further downstream in LS because the excess sediment created a smooth bed surface. In contrast, bedload tracers moved shorter distances in the YA, CC, and OG channels because they were trapped between cobbles and boulders as well as behind woody debris. In particular, most of the bedload tracers in the CC channel were trapped behind logging slash. Suspended sediment comprised < 50% of the total sediment yield for supply-limited conditions in the YA, CC and OG channels; in the LS channel, suspended sediment was > 60% of total sediment. Vegetation coverage and woody debris recruitment modified the available sediment and transport thresholds.

Episodic and chronic movement of sediment and woody debris (Chapter 5)

Both episodic and chronic sediment movement following basin wide clear-cut logging were compared in several channels within Maybeso Experimental Forest. Episodic events (landslides and debris flows in 1961, 1979, and 1993) resulted in the transport and redistribution of sediment and woody debris in headwater tributaries. Widespread landsliding in 1961 and 1993 was triggered by storms with recurrence intervals (based on 24-hour rainfall) of 7.0 and 4.2 years, respectively. The landslides that occurred in 1961 were likely related to the decreased root strength in headwater areas.

Between 300 and 1800 m^3 of sediment and woody debris were deposited in the lower reaches of headwaters after these mass failures. Landform features, such as incised channels, control the occurrence, distribution, and downstream effects of mass movements. Landslides and channelized debris flows formed log jams, alluvial fans, exposed reaches of bedrock, and abandoned channels. The terminus of the deposits did not enter main channels because channel gradients were less than 0.05 at the bottom of the U-shaped glaciated valley. Chronic sediment input to channels included surface erosion on exposed glacial till (rain splash, sheet erosion, and freeze-thaw) and bank failures. Chronic bedload sediment transport during a large storm (recurrence interval of 24-hour precipitation $\leq$ 1.5 years) in a channel with recent landslides (failures in 1993) was 2 to 10 times greater and finer in composition when compared to the sediment transported in a young alder riparian channel that experienced a landslide in 1961.

Water, sediment, and organic matter cascades through channels and accumulates from hillslopes to streams within headwater systems due to episodic and chronic processes. Hydrogeomorphic linkages (material flows) between hillslopes and streams differ during episodic and chronic events. Strong hydrological coupling (e.g., subsurface flow) from hillslopes and streams can initiate episodic mass movement. Smaller bank failures and sheet erosion near stream channels may occur as chronic events and are directly coupled with channels. Such linkages changed with regeneration of riparian vegetation during recovery processes. In contrast to the processes in headwaters, routing processes of episodic and chronic events from the downstream portion of headwaters to the main channel were more dispersed because of changes in the channel gradient and valley width. Temporal variation of sediment movement as well as riparian conditions related to management and disturbance regimes are important factors in understanding material transport within headwaters. Spatial variation of the occurrence of landslides and debris flows in headwater systems as well as their downstream linkages are also critical for understanding material dynamics through channel networks.

Dynamics of sediment and woody debris in steep headwater streams: a synthesis

Timber harvesting and related landslides and debris flows clearly affect the dynamics of woody debris and sediment in headwater streams. Theses external influences (mass movement and timber harvesting) modified channel morphology and sediment transport processes compared to undisturbed old-growth conditions. Three aspects of disturbance appear to be important for understanding the dynamics of sediment and woody debris: (i) logging slash; (ii) landslides and debris flows; and (iii) regeneration of riparian stands after timber harvesting and mass movement. These conditional changes are important in headwater streams because of the strong coupling among hillslopes, zero-order basins, and stream channels. Such conditional changes with time affect the distribution of woody debris and sediment: this in turns modifies geomorphic attributes and sediment transport. Spatial and temporal variations in these conditional changes create the variation of material dynamics in headwater streams, and thus cause the variation of material transport from headwater to downstream systems.

This study found that the management and disturbance regimes clearly affect geomorphic processes and attributes related to woody debris and sediment. Sediment yield and routing in headwater streams can be described by variables related to the amount of sediment and woody debris input from hillslope to channels over time (Figure C.1). In old-growth streams, sediment yield remains low due to sediment-limited conditions with no significant sediment source from hillslopes. Large and fine woody debris as well as interlocked boulders contribute to sediment storage and channel step formation in old-growth channels. However, both timber harvesting and mass movement alter sediment and woody debris availability: this in turn modifies sediment yield and routing in the following ways:

1. After clear-cutting headwater catchments, inputs of logging slash significantly increase the abundance of in-channel woody debris (see stage 1 in Figure C.1a).
2. The logging slash initially stores sediment, creates channel steps, and reduces the sediment movement (stage 1 to 3 in Figure C.1b).

3. In the absence of landslides and debris flows, larger woody materials remain in the channel 50 to 100 years after logging and sediment transport remains low (before stage 3 in Figures C.1a and C.1b).
4. When landslides and debris flows occur 3 to 15 years after logging due to intense rain and deterioration of root strength (Sidle et al., 1985), woody debris is evacuated from headwater streams and deposited in downstream reaches (stage 2 in Figure C.1a).
5. Because of higher sediment production from stream banks in the scour zone, more bedload and suspended sediment is transported in channels affected by recent landslides and debris flows (after stage 2 in Figure C.1b).
6. Red alder stands actively re-colonize riparian zones of headwater streams for 20 to 50 years after mass movement and woody debris and organic materials are recruited from these stands, thus providing sediment storage sites (stage 2 to 4 in Figure C.1a and C.1b).
7. For the longer periods ranging from 100 to 200 years, late successional conifer riparian stands gradually replace in alder stands (stage 5 onwards in Figure C.1a) (Likens and Bilby, 1982).
8. Decoupling of geomorphic processes from hillslopes to channels due to vegetation coverage also reduces sediment inputs (stage 2 to 4 in Figure C.1b).

Thus, the recovery processes related to revegetation and woody debris recruitment significantly decrease sediment supply and transport in headwater streams.

Woody debris pieces and jams play important roles for altering physical processes and morphology in headwater streams. The function of woody debris is summarized as follows: (1) large woody debris is the primary determinate of channel form in headwater forest streams, particularly creating channel steps similar to boulder steps; (2) the presence of woody debris facilitates deposition and accumulation of sediment in channels; (3) functions of sediment storage and formation of steps modify the amount, material composition, and regimes of sediment movement; (4) higher numbers of woody debris pieces are important for storing sediment in headwaters; (5) large woody debris in stream channels can be stable and alter channel morphology for 50 to 200 years until the pieces decay or are transported by mass movement.

Timber harvesting may alter physical and biological processes in and around headwater streams for 100 years or more. Woody debris from logging may affect channel morphology for 200 years until the pieces decay or are transported by mass movement. In steep headwater systems, the probability of mass movement increases 3 to 15 years after logging. Mass movement modifies the availability of sediment and distribution of woody debris. In addition to the hydrologic and geomorphic changes related to timber harvesting, biological processes in headwater streams can be modified by changes in water temperature, solar radiation input, organic matter input, and sediment transport.

Headwater streams without fish have not been well managed compared to fish-bearing streams. Riparian buffer zones are not always appropriate for minimize harvesting impact on small headwater streams, because narrow riparian corridors are highly susceptible to windthrow. One possible management option is to plan timber-harvesting units based on drainage area of headwater systems. A headwater management unit is defined as a spatial extension of headwater systems. These units are delineated by the catchment boundary that includes the hillslopes and stream corridors along the headwater continuum. Headwater units could be delineated accordingly and managed sequentially or randomly throughout the watershed. If properly designed, such a temporal rotation system may minimize damage to the watershed by allowing various headwater systems to "blink-on" and "-off" in response to spatially and temporally distributed logging disturbances (Reeves et al., 1995). Such disturbances would have to be planned so as not to coincide with hydrologically active periods (Sidle et al., 2000). Another possible management options are "variable retention harvesting" around headwater channels (Franklin et al. 1997). Retained stands along headwater channels may contribute for shading streams, recruiting woody debris and organic matter, and inducing vegetation succession.

Conclusion

Understanding processes at various spatial and temporal scales is the fundamental approach to comprehend material dynamics related to hydrology, geomorphology, and biology. Depending on the objectives and approaches, scientists and managers observe and study hydrologic and geomorphic processes at different spatial and temporal scales: thus the explanations of results may also vary among the observations and studies. For instance, at short time scales, logging slash may be beneficial for storing sediment and reducing sediment yield in headwater channels. However, for longer time scales, accumulations of sediment due to logging slash recruitment may induce sequential failures of woody debris dams and subsequent debris flows. Thus, potential relationships between causes and responses at various temporal and spatial scales should be estimated to further improve our understanding of the dynamics in headwater streams.

Ecology and management of downstream riparian zones have been extensively studied and applied in the context of stream restoration during the past 10 years (Naiman et al., 2000). However, the role of headwater systems as sources of water, sediment, nutrients, and organic matter has attracted more attention with respect to restoring and managing downstream reaches. To enhance our understanding of the dynamics in headwater streams related to the influence of management and disturbance regimes, the following hydrologic, geomorphic, and biological processes need to be considered: (1) understanding establishment, growth, competition and mortality of riparian vegetation over time after timber harvesting and mass movement; (2) estimating soil in landslide scars and sediment accumulation in headwater channels with changes in riparian vegetation; and (3) comprehending subsurface flow paths, nutrient transformation, and frequency/magnitude of peak discharge with changes in riparian vegetation, soil development, and sediment accumulation in channels. Such studies will provide the necessary information for effective management and conservation of forested headwater streams and watersheds.

It is very difficult to attain a holistic understanding of material transport at various spatial and temporal scales as well as the effects of management and disturbance regimes on stream ecosystems.

Although this study examines and emphasizes the dynamics of sediment and woody debris throughout approximately 100 years, processes operating over much longer time scales need to be incorporated to develop a more complete conceptual model of material dynamics in headwater streams. For example, glaciation and Holocene climate changes are also important to evaluate and predict the dynamics of material transport. To advance towards a holistic understanding of geomorphic processes in headwater streams, it will be necessary to attempt to model the combinations of episodic and chronic processes at various spatial and temporal scales.

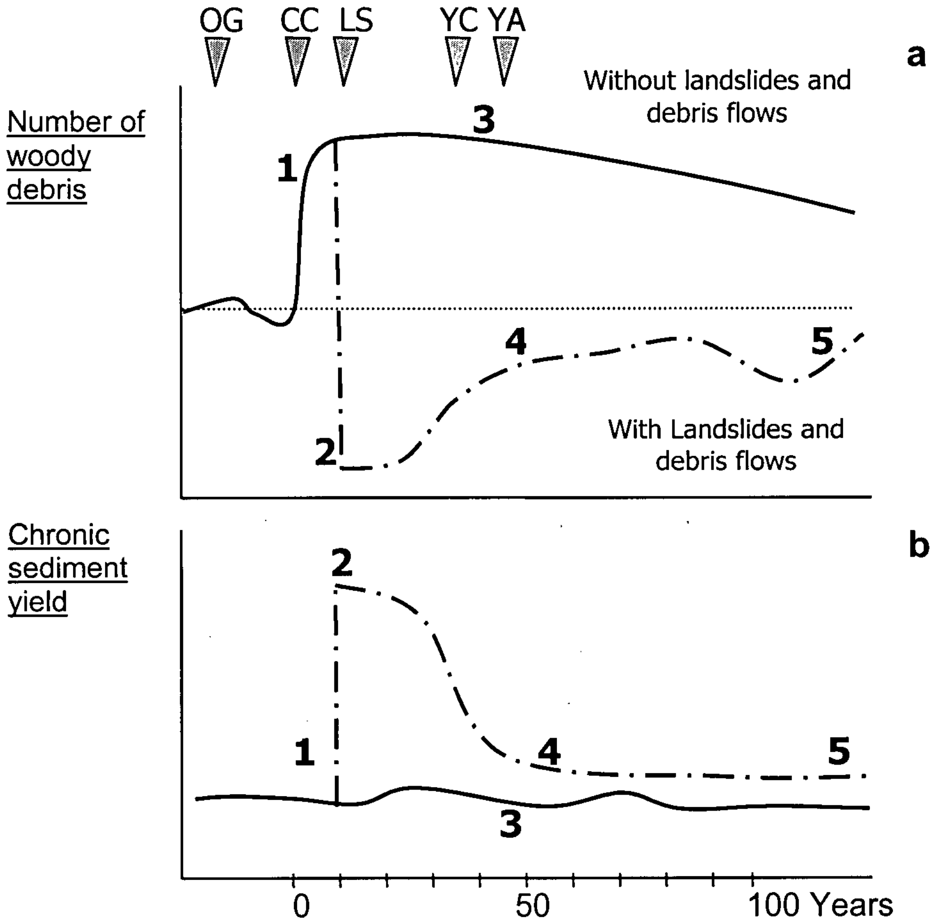


Figure C.1 Hypothetical change in the frequency of woody debris in headwater streams (developed from Likens and Bilby, 1982). The amount of woody debris and sediment changes with timber harvesting and related mass movement in the following way: (1) after clear-cut logging, logging slash enters streams and creates woody debris steps and dams; (2) landslides and debris flows transport woody debris and sediment to downstream reaches; (3) conifer riparian stands colonize after logging in sites without landslides and debris flows; (4) colonized alder stands begin to fall and enter streams after mass movement; (5) mature, late successional conifers, replace alder stands and began to interact with streams.

References

Abraham, A.D., Li, G., and Atkinson, J. 1995. Step-pool streams: adjustment to maximum flow resistance. Water Resources Research 31: 2593-2602.

Adenlof, K.A., and Wohl, E.E. 1994. Controls on bedload movement in a subalpine stream of the Colorado Rocky Mountains, USA. Arctic and Alpine Research 26: 77-85.

Anderson, N.H. 1997. Phenology of Trichoptera in summer-dry headwater streams in western Oregon, U.S.A. Pages 7-13 In Holzenthal RW, Flint Jr. OS, ed. Proceedings of the 8th International Symposium on Trichoptera. Ohio: Ohio Biological Survey.

Ashida, K., Egashira, S., Sawada, T., and Nishimoto, N. 1985. Geometric structures of step-pool bed forms in mountain streams. Disaster Prevention Research Institute Annuals, Kyoto University, 28(B-2): 325-335 (In Japanese).

Assani, A.A., and F. Petit. 1995. Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch. Catena 25: 117-126.

Beechie, T.J. 2001. Empirical predictors of annual bedload travel distance, and implication for salmonid habitat restoration and protection. Earth Surf. Processes Landforms 26: 1025-1034.

Benda, L.E. 1990. The influence of debris flow on channel and valley floor in the Oregon coastal range, U.S.A.. Earth Surf. Processes Landforms 14: 27-31.

Benda, L., and Dunne, T.. 1987. Sediment routing by debris flows. Pages 213-223 In Beschta RL, Blinn T, Grant GE, Ice GG, and Swanson FJ (eds), Erosion and sedimentation in the Pacific Rim, International Association of Hydrological Science Publication 165.

Benda, L.E., and Cundy, T.W. 1990. Predicting deposition of debris flows in mountain channels. Canadian Geotechnical Journal 27: 409-417.

Benda, L.E., and Dunne, T. 1997a. Stochastic forcing of sediment supply to channel networks from landslidiong and debris flows. Water Resources Research, 33: 2849-2863.

Benda, L., and Dunne, T. 1997b. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33: 2865-2880.

Berg, N., Carlson, A, and Azuma, D. 1998. Function and dynamics of woody debris in stream reaches in the central Sierra Nevada California. Can, J. Fish. Aquat. Sci. 55: 1807-1820.

Bilby, R.E., and Bisson, P.A. 1992. Allochthonous versus autochthonous organic matter contributions to the trophic support of fish populations in clear-cut and old-growth forested streams. Canadian Journal of Fisheries and Aquatic Sciences 49: 540-551.

Bilby, R.E., and Likens, G.E. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61: 1107-1113.

Bilby, R.E., and Ward J.W. 1989. Change in characteristics and function of woody debris with increasing size of stream in Western Washington. Trans. Am. Fish. Soc. 118: 368-378.

Bilby, R.E., and Ward, J.W. 1991. Characteristics and function of large woody debris in streams draining Old-growth, clear-cut, and second-growth forests in Southwestern Washington. Can. J. Fish. Aquat. Sci. 48: 2499-2508.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dollof, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K.V., and Sedell, J.R. 1987. Large woody debris in forest streams in the Pacific Northwest: Past, present, and future. *In* Stream management: forestry and fisheries interaction. Contribute 57. Edited by Salo, E.O. and Cundy, T.W., Institute of Forest Resources, University of Washington, Seattle, Washington, 143-190pp.

Bovis, M.J., Millard, T.H., and Oden, M.E. 1998. Gully processes in Coastal British Columbia: the role of woody debris. In Carnation creek and Queen Charlotte Islands fish/forest interaction workshop: Applying 20 years of coastal research to management solution. *Edited by* Hogan, D.L., Tschaplinski, P.J., and Charwin, S. B.C. Min. For., Res. Br., Victoria, B.C. Land Manage. Handb. No.41: 49-75.

Bravard, J.P., and Gilvear, D.J. 1996. Hydrological and geomorphological structure of hydrosystems. Page 89-116, In Petts, G.E., and Amoros, C. eds. Fluvial Hydrosystems, London: Chapman and Hall.

Bristow, C.S., Best, J.L., and Roy, A.G. 1993. Morphology and facies models of channel confluence. In Marzo, M, Puigdefabregas C, ed. Alluvial sedimentation. Special publication number 17 of the International Association of Sedimentologists. Oxford: Blackwell Scientific Publications.

Bromann, B.T., and Sidle, R.C. 1990. Changes in productivities and distribution of nutrients in a chronosequence at Glaicer Bay National Park, Alaska. Journal of Ecology 78: 561-568.

Bryant, M.D. 1980. Evolution of large organic debris after timber harvesting: Maybeso Creek, 1949-1978. USDA Forest Service, Gen. Tech. Rep. PNW-101.

Bryant, M.D. 1984. Distribution of salmonids in the Trap bay basin, Tenakee inlet. *In* Fish and wildlife relationships in old-growth forests: Proceedings of a symposium held in Juneau, Alaska 12-15 April 1982. *Edited by* Meehan, W.R., Merrell Jr., T.R., and Hanley, T.A. Ameri. Inst. Fish. Res. Biol.: 17-31.

Buffington, J.M., and Montgomery, D.R. 1999a. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resour. Res. 35: 3507-3521.

Buffington, J.M., and Montgomery, D.R. 1999b. Effects of sediment supply on surface textures of gravel-bed rivers, Water Resour. Res. 35: 3523-3530.

Caine, N, and Swanson FJ. 1989. Geomorphic coupling of hillslope and channel systems in two small mountain basins. Zeitschrift fur Geomorpholgie N.F. 33: 189-203.

Campbell, A.J., and Sidle, R.C., 1985. Bedload transport in a pool-riffle sequence of a coastal Alaska stream, Water Resour, Bull., 21, 579-590.

Carling, P. 1988. The concept of dominant discharge applied to gravel-bed streams in relation to channel stability threshold. Earth Surface Processes and Landforms 13: 355-367.

Chartrand, S.M., and Whiting, P.J. 2000. Alluvial architecture in headwater streams with special emphasis on step-pool topography. Earth Surf. Processes Landforms 25: 583-600.

Chin, A. 1989. Step pools in stream channels. Progress in Physical Geography 13: 391-407.

Chin, A. 1997. On the stability of step-pool mountain streams. J. Geology 106: 59-69.

Chin, A. 1999. The morphologic structure of step-pools in mountain streams. Geomorphology 27: 191-204.

Church, M. 1996. Channel morphology and typology. Pages 185-202 In Petts G, Calow P, ed. River Flow and Channel Forms. Oxford: Blackwell Science.

Church, M., and Mark, D.M. 1980. On size and scale in geomorphology. Progress in Physical Geography 4: 342-390.

Church, M., Wolcott, J.F., and Fletcher, K. 1991. A test of equal mobility in fluvial sediment transport: behavior of the sand fraction, Water Resour. Rese. 27: 2941-2951.

Church, M., and Hassan, M.A. 1992. Size and distance of travel of unconstrated clasts on a streambed, Water Resour. Res. 28: 299-303.

Church, M., Hassan, M.A., and Wolcott, J.F. 1998. Stability self-organized structures in gravel-bed stream channels: field and experimental observation. Water Resour. Res. 34: 3169-3179.

Commandeur, P.R., Guy, B.T., and Hamilton, H. 1996. The effects of woody debris on sediment fluxes in small coastal stream channels, *Information Report BC-X-367*, Pacific Forestry Centre, Canadian Forest Service, Victoria, British Columbia, 28pp.

Cummins, K.W., Sedell, J.R., Swanson, F.J., Minshall, G.W., Fisher, S.G., Cushing, C.E., Petersen, R.C., and Vannote, R.L. 1983. Organic matter budgets for stream ecosystems: Problems in their evaluation. Pages 279-298 in Barnes JR, Minshall GW, ed. Stream Ecology: Application and testing general ecological theory. New York and London: Plenum Press.

Cummins, K.W., Wilzbach, M.A., Gates, D.M., Perry, J.B., and Taliaferro, W.B. 1989. Shredders and riparian vegetation. BioScience 39: 24-30.

Dhakal, A.S., and Sidle, R.C. *in press*. Distributed simulation of landslides for different rainfall scenario. Hydrological Processes.

Dieterich, M., and Anderson, N.H. 1998. Dynamics of abiotic parameters, solute removal and sediment retention in summery-dry headwater streams of western Oregon. Hydrobiologia 379: 1-15.

Dieterich, M., and Anderson, N.H. 2000. The invertebrate fauna of summer-dry streams in western Oregon. Archive fur Hydrolobiogie 147: 273-295.

Dietrich, W.E., and Dunne, T. 1978. Sediment budget for small catchment in mountainous terrain. Zeitschrift fur Geomorphologie N.F. Suppl. Bd. 29: 191-206.

Dietrich, W.E., Krichner, J.W., Ikeda, H., and Iseya, F. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, Nature, 340, 215-217.

Duckson, Jr. D.W., and Duckson, L.J. 2001. Channel bed steps and pool shapes along Soda Creek, Three Sister Wilderness, Oregon. Geomorphology 38: 267-269.

Dunne, T. 1990. Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow. Pages 1-28 In Higgins CG, Coates DR ed. Ground water geomorphology. Geological Society of America Special Paper 252.

Dunne, T. 1991. Stochastic aspect of the relations between climate, hydrology and landform evolution. Transactions, Japanese Geomorphological Union 12: 1-24.

Ferguson, R.I., Perstegaard, K.L., and Ashworth, P.J. 1989. Influence of sand on hydraulic and gravel transport in a braided gravel bed river. Water Resour. Res. 25: 635-643.

Fisher, S.G. 1997. Creativity, idea generation, and the functional morphology of stream. Journal of the North American Benthological Society 16: 305-318.

Frissell, C.A., Liss, W.J., Warren, C.E., and Hurley, M.D. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10: 199-214.

Franklin, J.F., Berg, D.R., Thornburgh, D.A., and Tappeiner, J.C. 1997. Alternative silvicultural approaches to timber harvesting: variable retention harvesting systems. In Kohm K.A., and Franklin J.F. eds. Creating a Forestry for 21st century: The Science of ecosystem management. Island Press, Washington D.C. 111-140pp.

Froehlich, H.A. 1973. Natural and man-caused slash in headwater streams. Pacific logging congress Logging Handb. XXXIII. Pacific Logging Congr., Portland Oregon.

Gintz, D., Hassan, M.A., and Schmidt, K. 1996. Frequency and magnitude of bedload transport in a mountain river. Earth Surface Processes and Landforms 21: 433-445.

Gomi, T., Sidle, R.C., Bryant, M.D., and Woodsmith, R.D. 2001. Characteristics of woody debris and sediment in headwater streams, southeast Alaska. Can. J. For. Res. 31: 1386-1399.

Grant, G.E., and Wolff, A.L. 1991. Long-term patterns of sediment transport after timber harvesting, western Cascade, mountains, Oregon. In *Sediment and stream water quality in a changing environment: trends and explanation*. Peters NE, Walling DE (eds). International Association of Hydrological Scinece (IAHS), publication 203; 31-40.

Grant, G.E., Swanson, F.J., and Wolman, M.G. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geol. Soc. Am. Bull. 102: 340-352.

Gregory, K.J., and D.E. Walling, Drainage basin from and processes, John Wiley and Sun, New York, 1973.

Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystems perspective of riparian zones. BioScinece 41: 540-551.

Hack, J.T., and Goodlett, J.C. 1960. Geomorphology and Forest Ecology of a mountain region in the Central Appalachians. US Geological Survey Professional Paper 347: 66p. Washington DC.

Halwas, K.L., and Church, M. 2002. Channel units in small, high gradient streams on Vancouver Island, British Columbia. Geomorphology 43: 243-256.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. in Ecol. Res. 15: 133-302.

Harris, A.S., and Farr, W.A. 1974. The forest ecosystem of southeast Alaska: 7. Forest ecology and timber management. USDA Forest Service Gen. Tech. Rep. PNW-25.

Harvey, A.M. 2001. Coupling between hillslope and channels in upland fluvial systems: implications for landscape sensitivities, illustrated from Howgill Fells, northwest England. *Catena* **42**: 225-250.

Heard, S.B., and Richardson, J.S. 1995. Shredder-collector facilitation in stream detrital food webs: is there enough evidence? Oikos 72: 359-366.

Hedman, C.W., Van Lear, D. H., and Swank, W.T. 1996. In-stream large woody debris loading and riparian forest serial stage associations in the southern Appalachian mountains. Can. J. For. Res. 26: 1218-1227.

Hedin, L.O., Mayer, M.S., and Likens, G.E. 1988. The effect of deforestation on organic debris dams. Verh. Internat. Verein. Limnol. 23: 1135-1141.

Heede, B.H. 1972. Influence of a forest on hydraulic geometry of two mountain streams. Water Resour. Bull. 8: 523-530.

Hewlett, J.D., and Hibbert, A.R. 1967. Factor affecting the response of small watersheds to precipitation in humid area. Pages 275-290, In Sopper WE, and Lull HW eds, Forest Hydrology, Oxford, Pergamon Press.

Hey, R.D. 1979. Dynamic process-response model of river channel development. Earth Surface Processes 4: 59-72.

Hogan, D.L., Bird, S.A., and Haussan, M.A. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: the influence of forest management on channel morphology and fish habitat. 4th international workshop on gravel bed rivers, August 20-26, Gold Bar, Washington, USA.

Hogan, D.L., Bird, S.A., and Rice, S. 1998. Stream channel morphology and recovery processes. In Carnation Creek and Queen Charlotte Islands Fish/Forest Workshop: Applying 20 years of coast research to management solutions. Hogan DL, Tschaplinski PJ, Chatwin S (eds). British Columbia, Ministry of Forestry, Research Branch, Victoria, B.C., Land Management Handbook No. 41: 77-96.

Hutton, J. 1795. Theory of the earth. Edinburgh, London.

Hynes, H.B.N. 1975. The stream and its valley. Verhandlungen der Internationale Vereinigung fur Theoretische und Augewandte Limnologie 19: 1-15.

Inoue, M., and Nakano, S. 1998. Effects of woody debris on the habitat of juvenile masu salmon (*Oncorhynchus masou*) in north Japanese streams. Freshwater Biology 40: 1-16.

Johnson, A.C., Swanston, D.N., and McGee, K.E. 2000. Landslide initiation, runout, and deposition within clearcuts and old-growth forests of Alaska, J. American Water Resources Association 36: 1-14.

Johnson, B.L., Richardson, W.B., and Naimo, T.J. 1995. Past, present and future concepts in large river ecology. BioScience 45: 134-141.

Jackson, W.L., and Beschta, R.L. 1982. A model of two-phase bedload transport in an Oregon coast range stream. Earth Surf. Processes Landform 7: 517-527.

Komar, P.D., and Shih, S.M. 1992. Equal mobility versus changing bedload grain sizes in gravel-bed streams, In *Dynamics of gravel-bed rivers*, edited by Billi, P., R.D. Hey, C.R. Thorne, and P. Tacconi, John Wiley and Sons, New York, 73-107pp.

Kiffney, P.M., Richardson, J.S., and Feller, M.C. 2000. Fluvial and epilithic organic matter dynamics ub geadwater streams of southwestern British Columbia, Canada. Archive für Hydrobiologie 148: 109-129.

Kirkby, M.J. 1993. Network hydrology and geomorphology. Pages 1-11 In Beven K, Kirkby MJ, ed. Channel network hydrology. New York: John Wiley and Sons.

Lamberti, G.A, Gregory, S.V., Ashkenas, L.R., Wildman, R.C., and Moore, K.M. 1991. Stream ecosystem recovery following a catastrophic debris flow. Canadian Journal of Fisheries and Aquatic Sciences 48: 196-208.

Lenzi, M.A. 2001. Step-pool evolution in the Rio Cordon, northeastern Italy. Earth Surf. Processes Landforms 26: 991-1008.

Lenzi, M.A., and Marchi, L. 2000. Suspended sediment load during floods in a small stream of the Dolomites (northern Italy). Catena 39: 267-282.

Leopold, L.B., Wolman, M.G., and Miller, J.P. 1964. Fluvial Processes in Geomorphology. New York: Dover Publications.

Likens, G.E., and Bilby, R.E. 1982. Development, maintenance, and role of organic debris dams in New England streams. In Sediment budgets and routing in Forested drainage basins. Edited by Swanson F.J., Janda, R.J., Dunne, T., Swanston, D.N. USDA Forest Service, Gen. Tech. Rep. PNW-141: 122-128.

Likens, G.E., Bormann, F.H., Pierce, R.S., Eaton, J.S., and Johnson, N.M. 1977. Biogeochemistry of a forested ecosystem. New York: Springer-Verlag.

Lisle, T.E. 1987. Channel morphology and sediment transport in steep streams, In *Erosion and sedimentation in the Pacific Rim*. edited by Beschta, R.L., T. Blinn, G.E. Grant, F.J. Swanson, and G.G. Ice, IAHS publication No. 165, 287-297pp, Covarllis, Oregon.

Lisle, T.E. 1995. Particle size variation between bed load and bed material in natural gravel bed channels. Water Resour. Res. 31: 1107-1118.

Lisle, T.E., and Hilton, S. 1992. The volume of fine sediment in pools: an index of sediment supply in gravel-bed streams. Water Resources Bulletin, 28, 371-383.

Littell, R.C., Milliken, G.A., Stroup, W.W., and Wolfinger, R.D. 1999. SAS system for mixed models. SAS institute Inc., Cary, NC.

Maita, H., 1996. Deformation of step-pool bedform by passing of a sediment wave. Journal of the Japan Society of Erosion Control Engineering, 49: 21-27 (in Japanese with English abstract).

Megahan, W.F. 1982. Channel sediment storage obstruction in forested drainage basins draining the Granitic bedrock of Idaho basins. *In* Sediment budget and routing in forested drainage basins. *Edited by* Swanson, F.J., Janda, R.J., Dunne, T., and Swanston, D.N. USDA Forest Service Gen. Tech. Rep. PNW-141: 114-121.

Meehan, W.R., Farr, W.A., Bishop, D.M., and Patric, J.H. 1969. Effects of clear-cutting on Salmon habitat of two southeast Alaska streams. USDA Forest Service Res. Paper PNW-82.

Meyer, J.L., and Wallace, J.B. 2001. Lost linkages and lotic ecology: rediscovering small streams. In Press MC, Huntly NJ, and Levin S eds. Ecology: Achievement and challenge, Oxford: Blackwell Science, 295-317p.

Millard, T. 2000. Channel disturbance and logging slash in S5 and S6 streams – an examination of streams in the Nitinat Lake area, Southwest Vancouver Island -. BC Forest Service, Forest Research Tech. Rep. TR-005.

Minshall, G.W., Cummins, K.W., Peterson, R.C., Cushing, C.E., Bruns, D.A., Sedell, J.R., and Vannote, R.L. 1985. Development in stream ecosystem theory. Canadian Journal of Fisheries and Aquatic Sciences 42: 1045-1055.

Montgomery, D.R. 1999. Process domain and river continuum. Journal of the American Water Resources Association 35: 397-410.

Montgomery, D.R. Abbe, T.B., Buffington, J.M., Peterson, N.P. Schmidt, K.M., Stock, J.D. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381: 587-588.

Montgomery, D.R. and Buffington, J.M. 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109: 596-611.

Montgomery, D.R., and Buffington, J.M. 1998. Channel processes, classification, and response. Pages 13-42 In Naiman RJ, and Bilby RE, ed. River ecology and management: Lesson from the Pacific coastal ecoregion, New York: Springer-Verlag.

Montgomery, D.R., Buffington, J.M., Smith, R.D., Schmidt, K.M., and Pess, G. 1995. Pool spacing in forest channels. Water Resour. Res. 31(4): 1097-1105.

Montgomery, D.R., and Dietrich, W.E. 1989. Source areas, drainage density, and channel initiation.

Water Resources Research 25:1907-1918.

Montgomery, D.R., and Foufoula-Georgiou, E. 1993. Channel network source representation using Digital Elevation Model. Water Resources Research 29: 3925-3934.

Montgomery, D.R., Schmit, K.M., Greenberg, H.M., and Dietrich, W.E. 2000. Forest clearing and regional landsliding. Geology 28: 311-314.

Moog, D.B., and Whiting, P.J. 1998. Annual hystheresis in bedload rating curves. Water Resour. Res. 34: 2393-2399.

Murphy, M.L., Heifetz, J., Johnson, S.W., Koski, K.V., and Thedinga. 1986. Effects of Clear-cut logging with and without buffer strips on juvenile Salmonids in Alaskan streams. Can. J. Fish. Aqut. 43: 1521-1533.

Murphy, M.L., and Koshi, K.V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North Am. J. Fish. Management 9: 423-436.

Naiman, R.J., Bilby, R.E., and Bisson, P.A. 2000. Riparian ecology and management in the Pacific costal rain forest. BioScinece 50: 995-1011.

Nakamura, F. 1986. Analysis of storage and transport processes based on age distribution of sediment. Transactions, Japanese Geomorphological Union 7: 165-184.

Nakamura, F., Maita, H., Araya, T. 1995. Sediment routing analyses based on chronological changes in hillslope and riverbed morphology. Earth Surface Processes and Landforms 20: 333-346.

Nakamura, F., and Swanson, F.J. 1993. Effects of course woody debris on morphology and sediment storage in mountain stream system in western Oregon. Earth surface processes and landforms 18: 43-61p.

Nakamura, F., and Swanson, F.J. 1994. Distribution of coarse woody debris in a mountain stream, western Cascade region, Oregon. Can. J. For. Res. 24: 2395-2403.

Nakamura, F., Swanson, F.J., and Wondzell, S.M. 2000. Disturbance regimes of stream and riparian systems – a disturbance-cascade perspective. Hydrological Processes 14: 2847-2860.

Nanson, G.C. 1974. Bedload and suspended-load transport in a small, steep, mountain streams. Ame. J. Sci, 274: 471-486.

Hassan, M.A., and Church, M. 2001. Sensitivity of bed load transport in Harris Creek: Seasonal and spatial variation over a cobble-gravel bar. Water Resources Research 37: 813-825.

Neter, J., Kutner, M.H., Nachtsheim, C.J., and Wasserman, W. 1996. Applied linear statistical models: Forth Edition. WCB McGrew-Hill, Boston.

Newbold, J.D., Elwood, J.W., O'Neill, R.V., and Van Winkle, W. 1982. Nutrient spiraling in streams: implications for nutrient limitation and invertebrate activities. American Naturalist 120: 628-652.

O'Conner, M.D. 1993. Bedload transport processes in steep tributary streams, Olympic peninsula, Washington USA. In Advances in hydro-science and –engineering, Volume1, edited by Yang, S.S.Y., Washington, D.C., pp 243-250.

Parker, G., Klingeman, P.C., and McLean, D.L. 1982. Bedload and size distribution in paved gravel-bed streams, J. Hydraul. Eng., 108, 544-571.

Pringle, C.M., Naiman, R.J., Bretschko, G., Karr, J.R., Oswood, M.W., Webster, J.R., Welcomme, R.L., and Winterbourn, M.J. 1988. Patch dynamics in lotic systems: the stream as a mosaic. Journal of the North American Bentholological Society 7: 503-524.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel morphology and woody debris in logging and unlogging basins of western Washington. Can. J. Fish. Aquat. Sci. 51: 37-51.

Reid, I., Frostick, L.E., and Layman, L. 1985. The incidence and nature of bedload transport during flood flows in coarse-grained alluvial channel, Earth Surf. Processes Landforms, 10, 22-44.

Reneau, S.I., Dietrich, W.E., Donahue, D.J., Jull, A.J.T., and Rubin, M. 1990. Late quaternary history of colluvial deposition and erosion in hollows, central California Coast Ranges. Geological Society of America Bulletin 102: 969-982.

Reeves, G.H., Benda, L.E., Burnett, K.M., Bisson, P.A., and Sedell, J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitat of evolutionarily significant units of anadromous salmonid in the Pacific Northwest. Pages 334-349 In Nielsen JL, Powers DA, ed. Evolution and the aquatic ecosystem: Defining unique units in population conservation. American Fisheries Society Symposium 17.

Reice, S.R., Wissmar, R.C., and Naiman, R.J. 1990. Disturbance regimes, resilience, and recovery of animal communities and habitat in lotic ecosystems. Environmental Management 14: 647-659.

Rice, S.P., Greenwood, M.T., and Joyce, C.B. 2001. Tributaries, sediment sources, and longitudinal organization of macroinvertebrate fauna along river systems. Canadian Journal of Fish and Aquatic Science 58: 824-840.

Richardson, J.S. 1991. Seasonal food limitation of detritivores in a montane stream: an experimental test. Ecology 72: 873-887.

Richardson, J.S. 1992. Food, microhabitat, or both?: macroinvertebrate use of leaf accumulations in a montane stream. Freshwater Biology 27: 169-176.

Richardson, J.S., and Neill, W.E. 1998. Headwater amphibians and Forestry in British Columbia: Pacific Giant Salamanders and Tailed Frogs. Northwest Science 72, Special Issue 2: 122-123.

Rickenmann, D. 1997. Sediment transport in Swiss torrents. Earth Surf. Processes Landforms 22: 937-951.

Rickenmann, D. 2001. Comparison of bed load transport in torrents and gravel bed streams, Water Resour. Res., 12, 3295-3305.

Rickenmann, D., D'Agostino, V., Fontana, G.D., Lenzi, M., and Marchi, L. 1998. New results from sediment transport measurement in two alpine torrents, In *Hydrology, water resources, and ecology in headwaters*, IAHS publication No. 248, 283-289pp.

Roberts, R.G., and Church, M. 1986. The sediment budget in severely disturbed watershed, Queen Charlotte Ranges, British Columbia. Canadian Journal of Forest Research 16: 1092-1106.

Robison, E.G., and Beschta, R.L. 1990. Characteristics of coarse woody debris for several coastal streams of southeast Alaska, USA. Can. J. Fish. Aquat. Sci. 47: 1684-1693.

Robinson, J.S., Sivapalan, M., and Snell, J.D. 1995. In the relative roles of hillslope processes, channel routing and network geomorphology in the hydrologic response of natural catchment. Water Resources Research 31: 3089-3101.

Rot, B.W., Naiman, R.J., and Bilby, R.E. 2000. Stream channel configuration, landform, and riparian forest structure in the Cascade Mountain, Washington. Can. J. Fish. Aquat. Sci. 57: 699-707.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey, Geological Society of America Bull., 67, 597-646.

Schumm, S.A., and Lichty, R.W. 1965. Time, space and causality in geomorphology. American Journal of Science 263: 110-119.

Schwab, J.W. 1998. Landslides on the Queen Charlotte Islands: Processes, rates and climatic events. In Carnation Creek and Queen Charlotte Islands Fish/Forest Workshop: Applying 20 years of coast research to management solutions. Hogan DL, Tschaplinski PJ, Chatwin S (eds). British Columbia, Ministry of Forestry, Research Branch, Victoria, B.C., Land Management Handbook No. 41: 41-47.

Sedell, J.R., Reeves, G.H., Hauer, F.R., Stanfrod, J.A., and Hawkins, C.P. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. Environmental Management 14: 711-724.

Shimokawa, E. 1984. A natural recovery process of vegetation on landslide scars and landslide periodicity in forested drainage basin: Proceeding of symposium on Effects of forest land use on erosion and slope stability, Hawaii, 99-107.

Sidle, R.C. 1984. Shallow groundwater fluctuations in unstable hillslopes in coastal Alaska. Zeitschrift fur Gletscherkunde und Glazialgeoleologie 20: 79-95.

Sidle, R.C. 1986. Seasonal pattern of allochthonous debris in three riparian zones of a coastal Alaska drainage. Watershed Research prospectives (Correll, D.L. ed.) Smithsonian institution press, Washington. 283-304.

Sidle, R.C. 1988. Bedload transport regime of a small forest stream. Water Resources Research 24: 207-218.

Sidle, R.C. 2000. Watershed challenges for the 21st Century: A global perspective for Mountain Terrain. *In* Land stewardship in the 21st Century: the contributions of watershed management. Ffolliot P.F., Baker, M.B., Edminster, C.B., Dillon, M.C., and Mora, K.L., *Technical coordinators*. 2000 March 13-16; Tucson, AZ. Proc. Rocky Mountain Research Station RMRS-P-13, USDA Forest Service, Fort Collins, Colo.: 45-56.

Sidle, R.C., and Campbell, A.J. 1985. Patterns of suspended sediment transport in a Coastal Alaska stream. Water Resources Bulletin 21: 909-917.

Sidle, R.C., and Hornbeck, J.W. 1991. Cumulative effects: a broader approach to water quality research. Journal of Soil and Water Conservation 46: 268-271.

Sidle, R.C., Noguchi, S., Tsuboyama, Y., and Laursen, K. 2001. A conceptual model of preferential flow systems in forested hillslopes: evidence of self-organization. Hydrological Processes 15: 1675-1692.

Sidle, R.C., Pearce, A.J., and O'Loughlin, C.L. 1985. Hillslope stability and landuse. American Geophysical Union, Water resources monograph 11.

Sidle, R.C., Sasaki, S., Otsuki, M., Noguchi, S., and Baharuddin, K. *In press*. Sediment pathways in a tropical forest: effect of roads and skid trails. Hydrological Processes.

Sidle, R.C., and Sharma, A. 1996. Stream channel changes associated with mining and grazing in the Great Basin. Journal of Environmental Quality. 22: 1111—1121.

Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., and Shimizu, T. 2000. Streamflow generation in steep headwaters: a linked hydro-geomorphic paradigm. Hydrological Processes 14: 369-385.

Sidle, R.C., and Wu, W. 1999. Simulating effects of timber harvesting on the temporal and spatial distribution of shallow landslides. Zeitschrift fur Geomorpholgie N.F. 43: 185-201.

Slaymaker, O. 2000. Assessment of the geomorphic impact of forestry in British Columbia. AMBIO 29: 381-387.

Smith, R.D., Sidle, R.C., Porter, P.E., and Noel, J.R. 1993. Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream. J. Hydro. 152: 153-178.

Stanford, J.A., and Ward, J.V. 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporhic corridor. Journal of the North American Bentholølgical Society 12: 48-60.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union, 38: 913-920.

Swanson, F.J., Bryant, M.D., Lienkaemper, G.W., and Sedell, J.R. 1984. Organic debris in small streams, Prince of Wales Island, Southeast Alaska. USDA Forest Service Gen. Tech. Rep. PNW-166.

Swanson, F.J., and Dyrness, C.T. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade range, Oregon. Geology 3: 119-124.

Swanson, F.J., Kratz, T.K., Caine, N., and Woodmansee, R.G. 1988. Landform effects on ecosystem patterns and processes. BioScience 38: 92-98.

Swanson, F.J., Johnson, S.L., Gregory, S.V., and Acker, S.A. 1998. Flood disturbance in a forested mountain landscape. Bioscience 48: 681-689.

Swanston, D.N. 1967. Soil-water piezometry in a southeast Alaska landslide area. USDA Forest Service, Research Note PNW-68.

Swanston, D.N. 1970. Mechanics of debris avalanching in shallow till soils of southeast Alaska. USDA Forest Service, Research Paper PNW-103.

Swanston, D.N., and Swanson, F.J. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. In Geomorphology and engineering. Coates DR (ed). Halsted Press, Pennsylvania; 199-221.

Townsend, C.R., 1989. The patch dynamics concept of stream community ecology. Journal of the North American Benthological Society 8: 36-50.

Trimble, S.W. 1990. Geomorphic effects of vegetation cover and management: some time and space considerations in prediction of erosion and sediment yield. In *Vegetation and erosion: Processes and environment*. Thornes JB (eds). John Wily and Sons: Chichester; 55-65.

Tsuboyama, Y., Sidle, R.C., Noguchi, S., Murakami, S., and Shimizu, T. 2000. A zero-order basin – its contribution to catchment hydrology and internal hydrological processes. Hydrological Processes 14: 387-401.

Tsukamoto, Y., Ohta, T., and Noguchi, H. 1982. Hydrological and geomorphological study of debris slides on forested hillslope in Japan. IAHS, 137: 89-98.

Vannote, R.L., Minshall, M. G., Cummins, K.W., Sedell, J.R., and Cushing C.E. 1980. The river continuum concept. Can. J. Fish. Aquat. Sci. 37: 130-137.

Wallace, J.B., Eggert, S.L., Meyer, J.L, and Webster, J.R. 1999. Effects of resource limitation on a detrital-based ecosystem. Ecological Monographs 69: 409-442.

Wallace, J.B., Webster, J.R., Meyer, J.L. 1995. Influence of log additions on physical and biotic characteristics of a mountain streams. Can. J. Fish. Aquat. Sci. 52: 2120-2137.

Ward, J.V., and Stanford, J.A. 1983. The serial discontinuity concept of lotic ecosystems. Page 29-42 In Fontaine TD, Bartell SM, ed. Dynamics of lotic ecosystems. Ann Arbor (MI): Ann Arbor Science.

Ward, J.V., and Stanford, J.A. 1995. The serial discontinuity concept: extending the model to floodplain rivers. Regulated Rivers: Research and Management 10: 159-168.

Warburton, J. 1992. Observation of bed load transport and channel; bed changes in a proglacial mountain stream. Arctic and Alpine Research 24: 195-203.

Wemple, B.C., Swanson, F.J., and Jones, J.A. 2001. Forest roads and geomorphic process interaction, Cascade Range, Oregon. Earth Surf. Processes Landforms 21: 191-204.

Whiting, P.J., and Bradley, J.B. 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18: 603-612.

Whiting, P.J., Stamm, J.F., Moog, D.B., and Ondorff, R.L. 1999. Sediment-transport flows in headwater streams. Geol. Soc. Am. Bull. 111: 450-466.

Whittaker, J.G. 1987. Sediment transport in step-pool streams. *In* Sediment transport in gravel-bed rivers. *Edited by* Bathurst, J.C., and Hey, R.D. John Wiley and Sons: 545-570.

Whittaker, J.G., and Jaeggi, N.R. 1982. Origin of step-pool systems in mountain streams. Proc. Am. Soc. Civ. Engrs, J. Hydraul. Div., 108 (HY6), 758-773.

Wilcock, P.R. 1998. Two-fraction model of initial sediment motion in gravel-bed rivers, Science, 280, 410-412.

Wipfli, M.S. 1997. Terrestrial invertebrate as salmonid prey and nitrogen source in stream: contrasting old-growth and young-growth riparian forest in Southeast Alaska, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 54: 1259-1269.

Wipfli, M.S. and Gregovich, D.P. 2002. Invertebrate and detritus export from fishless headwater streams in southeast Alaska: implication for upland forest management and downstreams= fish-bearing habitat. Freshwater Biology xx: xx-xx (in press).

Wolman, M.G. 1954. A method of sampling coarse riverbed material. Trans. Am. Geophysical Union 35: 951-956.

Wolman, M.G. 1977. Changing needs and opportunities in the sediment field. Water Resources Research 13: 50-54.

Wolman, M.G, and Miller, J.C. 1960. Magnitude and frequency of forces in geomorphic processes, *J. Geol.* 68: 54-74.

Wohl, E.E. 2000. Substrate influence on step-pool sequences in the Christopher creek drainage, Arizona. J. Geology 108: 121-129.

Wohl, E.E., and Grodeck, T. 1994. Channel bed-steps along Nahal Yael, Negev desert, Israel. Geomorphology 9: 117-126.

Wohl, E., Madsen, S., and MacDonald, L. 1997. Characteristics of log and clast bed-steps in step-pool streams of northwestern Montana, USA. Geomorphology 20: 1-10.

Wood, E.F., Sivapalan, M., Beven, K., and Band, L. 1988. Effects of spatial variability and scale with implications to hydrologic modeling. Journal of Hydrology 102: 29-47.

Woods, R., Sivapalan, M., and Duncan, M. 1995. Investigating the representative elementary area concept: an approach based on field data. Hydrological Processes 9: 291-312.

Woodsmith, R.D., and Buffington, J.M. 1996. Multivariate geomorphic analysis of forest streams: implication for assessment of landuse impacts on channel condition. Earth surface processes and landforms 21: 377-393.

Woodsmith, R.D. and Swanson, F.J. 1997. The influence of large woody debris on forest stream geomorphology. *In* Proceedings of management of landscape disturbed by channel incision *Edited by* Wang, S.S.Y., Langedoen, E.J., and Douglas Shields Jr., F. Oxford campus in the

University of Mississippi, May 1997. 133-138p.

Ziegler, A.D., and Giambelluca, T.W. 1997. Importance of rural roads as source area for runoff in mountainous areas of northern Thailand. Journal of Hydrology 196: 204-229.

Ziemer, R.R., and Lisle, T.E. 1998. Hydrology. Page 43-62 In Naiman RJ, and Bilby RE, ed. River ecology and management: Lesson from the Pacific coastal ecoregion, New York: Springer-Verlag.

Zimmerman, A. and Church, M. 2001. Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. Geomorphology 40: 311-327.