Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed

by

John M. Faustini

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented April 27, 2000
Commencement June 2001

AN ABSTRACT FOR THE DISSERTATION OF

John M. Faustini for the degree of Doctor of Philosophy in Geology presented on April 27, 2000. Title: Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed.

Abstract Approved: Julia Allen Jones (signature)

Julia Allen Jones

This investigation explored how the magnitude, style, and frequency of channel adjustments vary spatially and over time within a 5th-order mountain watershed. Historical data sets, including repeated cross section surveys spanning up to 20 years at five sites on 2nd to 5th-order channels and streamflow records spanning up to 50 years, were supplemented by mapping and field reconnaissance activities.

The study had two major parts. The first focused on two adjacent, contrasting stream reaches to examine the influence of large woody debris (LWD) on channel morphology and channel response to peak flows in a 3rd-order stream. The upper reach flows through old-growth forest with abundant LWD, while the lower reach was clearcut in 1964-65 and contains little LWD. A 25-year flood in 1996 caused deposition upstream of LWD steps in the old-growth reach alternating with scour between steps, resulting in no net gain or loss of sediment within the reach, while extensive scour and coarsening of the bed occurred in the clearcut reach. These observations suggest that reach-scale channel response was strongly influenced by LWD abundance, but that response at finer scales depends critically on the details of the location and arrangement of LWD.

The second part of the study examined the dynamics of channel response to peak flows over two decades, and to two particular large floods during that period, in different portions of the channel network. The cross section data show that the streambed at the study sites is very stable, particularly in lower-order channels. Peak

flows that produced detectable change at 90% of cross sections—flows able to cause significant channel adjustments—recur approximately three times as frequently (every 6-7 years) in 4^{th} to 5^{th}-order Lookout Creek as in 3^{rd}-order Mack Creek (20-25 years). Flows that produced detectable change at 25% of cross sections are estimated to occur on average every 1.7 to 3.0 years at the study sites. It is estimated that if peak flows of all sizes were increased by only 10% due to anthropogenic impacts (e.g., logging) or climate change, the frequency of peak flows of a magnitude observed to produce significant channel adjustments would increase by approximately 30% in Lookout Creek and 60% in Mack Creek.

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APPROVED:

Major Professor, representing Geology

Chair of the Department of Geosciences

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

John M. Faustini, Author

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This dissertation marks the culmination of a learning experience that for me has been occasionally exhilarating, often trying, and ultimately very rewarding. It could not have happened without the help of a large number of people along the way.

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Table of Contents

Page

Table of Contents (continued)

Page

Table of Contents (continued)

Page

Table of Contents (continued)

List of Figures

List of Figures (continued)

List of Figures (continued)

List of Figures (continued)

List of Figures (continued)

Figure | Page

List of Figures (continued)

List of Tables

List of Tables (continued)

List of Appendices

List of Appendix Figures

List of Appendix Figures (continued)

List of Appendix Tables

List of Appendix Tables (continued)

Preface

The theme of this dissertation is stream channel response to peak flows in mountain watersheds. Unlike their better-studied lowland counterparts, which in their natural state are shaped almost entirely by fluvial processes, mountain streams are strongly influenced by external landforms and processes that interact with and constrain the fluvial processes operating within the stream channel. While large low-gradient floodplain rivers are typically able to significantly rework their channels on a nearly annual basis, in high-gradient mountain streams the presence of bedrock, coarse bed material, and other relatively immobile debris such as large boulders and logs can limit the ability of the stream to reshape its bed except in large, infrequent floods. Within mountain watersheds, spatial variations in geology and natural or anthropogenic disturbance (e.g., fire, logging, etc.) and systematic downstream trends in landscape and channel characteristics (such as slope and channel dimensions relative to the sediment and debris delivered to the stream) combine to created a complex mosaic of spatially varying landscape patterns and processes which influence stream channel response to peak flows. This study investigated how the magnitude, style, and frequency of channel adjustments to peak flows vary spatially and over time within a 5th-order mountain watershed.

The dissertation consists of two major parts, both of which draw upon historical data sets available at the H.J. Andrews Experimental Forest in the Western Cascades of Oregon, supplemented by additional field investigation by the author. The first half examines the role of large woody debris (LWD) in modifying stream channel structure and its response to a large flood (estimated recurrence interval of approximately 25 years) in February 1996 by comparing channel morphological characteristics and the response of the channel as measured by repeated cross section surveys in two nearly adjacent, contrasting reaches of a 3rd-order stream within the Andrews Forest. The upper reach flows through an old-growth Douglas-fir/Western Hemlock forest and contains abundant LWD, including several channel-spanning LWD accumulations. The lower reach, located immediately downstream, was clearcut in 1964-65 and contains very little LWD. The availability of pre- and post-flood cross section, LWD inventory, and bed material particle size data made it possible to treat the February 1996 flood as a fortuitous "experiment" to test hypotheses about how LWD influences channel response to floods at the reach to within-reach scales.

The second half of the dissertation examines channel response to a wide range peak flows over a larger spatial and temporal scale. It draws on up to 50 years of streamflow data and 20 years of quasi-annual cross section monitoring data to explore the dynamics of stream channel response to peak flows at five 2^{nd} to 5^{th}-order stream reaches within the 64-km^2 Andrews Forest. This unique data set provided an opportunity to evaluate how frequency of channel adjustment and the relationship between peak flow magnitude and channel response vary between streams of different order within a single watershed in which both the natural history and land management activities have been well documented. This part of the study examined watershed scale patterns in channel response to peak flows, with particular attention to differences between 2^{nd} to 3^{rd}-order tributaries and 4^{th} to 5^{th}-order "mainstem" channels, in order to test recent hypotheses proposed in the geomorphology literature.

Stream Channel Response to Peak Flows in a Fifth-Order Mountain Watershed

Part I. Influence of Large Woody Debris on Channel Morphology and Response to Floods in a Third-Order Stream at the Reach to Within-Reach Scales

1 Introduction

Much has been learned in the past 25 years about the importance of large woody debris (LWD) as a geomorphic agent in forested mountain streams. LWD strongly influences channel morphology, regulates sediment storage and transport, and thereby affects the nature, magnitude, frequency and rate of channel change in response to floods and other channel-structuring events (e.g., landslides, debris flows, etc.). This study exploits a unique combination of long-term data sets on channel morphology and on LWD distribution and movement to investigate the interaction between LWD distribution and movement, channel morphology, and channel dynamics in a forested 3^{rd}-order mountain stream in the Western Cascades of Oregon.

The scale-dependence of the hydraulic, morphologic, and ecological functions of LWD in stream channels has long been recognized (Keller and Swanson, 1979; Marston, 1982; Harmon et al., 1986). This scale dependence leads to a large array of potential LWD influences on channel morphology and process. In their study of a mountain stream system in the Cascade Range of Oregon (which included the stream studied in this investigation), Nakamura and Swanson (1993) found that the effects of LWD on channel morphology and sediment storage changed systematically in moving from small to large channels. For example, LWD caused channel widening in all channels, but the mechanism of widening changed from predominantly sediment accumulation in small (1^{st} to 2^{nd}-order) channels, to sideslope failure in combination with sediment accumulation in medium (3^{rd} to 4^{th}-order) channels, to bank erosion in larger (5^{th}-order) channels. Similarly, LWD constitutes an important sediment storage control in 1^{st} to 5^{th}-order channels, but relative magnitude and duration of sediment storage associated with LWD is less for larger channels which are able to mobilize their bed load more frequently and to periodically redistribute LWD within the channel. In general, the amount of LWD (mass per unit channel area) decreases with increasing stream size (Keller and Swanson, 1979; Bilby and Ward, 1991). However, the influence on channel morphology and process is greatest in intermediate-size streams, which are large enough to periodically redistribute much of their LWD load and create channel-spanning accumulations of LWD, finer organic debris, and sediment in structures variously referred to in the literature as debris jams (Keller and Swanson, 1979), debris dams (Bilby, 1981), log steps (Marston, 1982), or coarse woody debris (CWD) jams (Nakamura and Swanson, 1993).

This study examines the influence of LWD on channel morphology and on channel response to a large flood in February 1996 (recurrence interval of approximately 25 years) in two adjacent, contrasting reaches of a single 3rd-order stream. The upper reach lies within old-growth conifer forest and contains abundant LWD, including many channel-spanning pieces. The lower reach was clearcut approximately 25 years ago and has almost no LWD within the channel. This strong contrast between the two reaches, in combination with the availability of pre- and post-flood cross section surveys and LWD inventory data, makes it possible to treat the February 1996 flood as a fortuitous, un-replicated experiment. Specific objectives of the study included the following:

1. Characterize differences in channel morphology between the old-growth and clearcut reaches and how these differences are related to differences in the quantity, size, or arrangement of LWD within the channel.
2. Assess differences in channel response to the flood of February 1996 (estimated recurrence interval of approximately 25 years).
3. Make inferences about how LWD modifies channel response to large floods in a steep, 3rd-order stream.
4. Compare the influence of static LWD on channel response to the February 1996 flood with that of LWD that was newly input or was moved during the flood.

The analysis was guided by several specific hypotheses, which include the following:

1. LWD increases hydraulic roughness and hence decreases flow velocity for a given discharge; therefore, LWD promotes channel stability at the reach scale.
2. At finer scales, LWD creates a diversity of hydraulic environments. Therefore, a reach that contains abundant LWD should exhibit greater within-reach spatial variability in bed material texture, bed slope, and channel response to a flood than a reach with little LWD.
3. By increasing hydraulic roughness and providing sediment storage sites that may be stable even at high flows, channel-spanning LWD accumulations increase the sediment storage potential of the channel and decrease bedload transport efficiency.
4. An implication of the preceding claims is that, all else being equal, a reach with abundant channel-spanning LWD should exhibit finer bed material texture, on average, than a reach with little LWD.

The bases for these hypotheses are discussed further in the following section.

2 Literature Review

2.1 Influence of LWD on Channel Morphology

The potential influence of LWD on channel morphology and habitat depends on its position with respect to the channel. Robison and Beschta (1990) developed a 4-zone classification of LWD position relative to the channel. In order of decreasing frequency of interaction with flows and generally decreasing significance to channel morphology, the four zones are:

zone 1: within the low-flow active channel,

zone 2: within the bankfull active channel outside or suspended above low-flow channel,

zone 3: suspended above bankfull stage within the bankfull channel width, and

zone 4: laterally outside the bankfull channel.

Morphologic influences of LWD can be divided into effects on channel planform, longitudinal profile, and bed material texture. LWD can trigger either abrupt or chronic changes in channel planform and position. Examples of abrupt changes include meander cutoffs or lateral switching of flow into secondary or abandoned channels due to blockage of the main channel (Keller and Swanson, 1979). Chronic changes associated with LWD include accelerated lateral migration due to deflection of flow against the bank (Harmon et al., 1986) or growth and stabilization of bars and islands (Montgomery et al., 1995). Planform changes are generally limited to larger, relatively low-gradient streams which are not highly constrained by adjacent hillslopes.

LWD may also control the location and frequency of pools and riffles and reach-level morphology. Montgomery and Buffington (1997) argue that LWD can force a pool-riffle morphology in a channel that would otherwise have a plane-bed morphology lacking in pools or riffles. In a survey of several streams in southeast Alaska and Washington, Montgomery et al. (1995) found that pool spacing was inversely proportional to frequency of LWD pieces in pool-riffle, plane-bed, and forced pool-riffle channels, but was unrelated to LWD frequency in steeper step-pool channels.

A commonly reported and readily observable effect of channel-spanning LWD accumulations is an increase in channel width due to bank erosion and/or sediment deposition within the channel (Keller and Swanson, 1979; Keller and Tally, 1979; Hogan, 1985). Less well documented is the effect of LWD on the variability of channel width. Zimmerman et al. (1967) found that the variation in channel width was greater in forested reaches than non-forested, sod-bank reaches in small watersheds (<6 km^2) in the Sleepers River basin of New Hampshire, which they attributed to LWD in the channel and tree root mats on the bank, but the influence of LWD on variability of channel width in larger channels was minimal. Nakamura and Swanson (1993) reported that variance in width in Mack Creek, a 3rd order stream in the western Oregon Cascades, was least for bedrock-controlled sections, where LWD had little effect on channel morphology, and was greater for sections with large LWD capable of spanning the channel than for sections without appreciable LWD. Variance in width was greatest where channel spanning debris jams were present.

In headwater streams occupying narrow, steep-sided valleys, the morphologic influence of LWD is expressed by the creation of a stepped longitudinal channel profile rather than through effects on channel planform geometry (Keller and Swanson, 1979; Nakamura and Swanson, 1993; Montgomery et al, 1995). The values reported in the literature for the proportion of channel fall controlled by LWD vary widely, from an average of 6% for 1st to 5th order channels in the Oregon Coast Range (Marston, 1982) to as much as 100% for headwater streams of the Rocky Mountains of Colorado and the White Mountains of Arizona (Heede, 1972a, 1972b, 1977). The degree to which LWD controls the stream profile is largely determined by the size of the LWD relative to the channel and the ability of the channel to bypass obstructions (Harmon et al., 1986). Bilby (1981) found that the percentage of channel fall controlled by LWD decreased systematically with increasing stream order in the Hubbard Brook Experimental Forest in New Hampshire, from 52% for 1st order streams to 46% and 10% for 2nd and 3rd order streams, respectively. Marston (1982) found a more complex pattern in a survey of 163 km of 1st through 5th order streams in the Oregon Coast Range, where the frequency of LWD-controlled steps in the channel profile reached a maximum of 4 per km for 3rd order channels but the total fall was greatest for 4th order channels due to larger average step size.

Another reported effect of LWD on the longitudinal profile of stream channels is to increase the variance in depth along the channel thalweg and in pools (Hogan, 1985; Lisle, 1995). Lisle (1995) found that variance of residual depth along the channel thalweg decreased significantly after total removal of LWD from low-sinuosity reaches in a low-gradient stream with high wood loading from the 1980 eruption of Mt. St. Helens, but variance in residual depth changed little in two higher sinuosity reaches from which LWD was removed. Longitudinal variance in channel depth has been shown to be strongly positively correlated to salmonid population in some streams (Bienz, 1998).

It might be anticipated that the creation of a stepped longitudinal profile by LWD, with its implied alternation of low-and high-gradient channel segments, would be accompanied by a corresponding variation in bed material particle size, with a fining of bed material upstream of steps and a coarsening downstream as has been reported by Chin (1989) for boulder steps. Although such a pattern is readily observable in the field, surprisingly few published reports have documented it. However, particle-size data showing a pattern of bed material enriched in fine particles upstream of channel-spanning LWD structures and relatively depauperate of fines downstream have recently been reported for low order streams in the Queen Charlotte Islands of British Columbia (Rice and Church, 1996) and in Vermont (Thompson, 1995).

2.2 Influence of LWD on Sediment Storage and Transport

LWD also profoundly influences sediment storage and transport. Several researchers have found that LWD structures comprise the dominant sediment storage sites in at least some steep forested mountain streams (Megahan and Nowlin, 1976; Thompson, 1995; Montgomery et al., 1996). Montgomery et al. (1996) found that LWD can cause alluvial channels to exist where bedrock channels would otherwise be expected due to high bed shear stress and low sediment supply. Other workers have estimated that individual pieces or accumulations of LWD create storage sites for sediment accumulations amounting to as much as 10 to 15 times the annual sediment yield of some mountain streams (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Megahan, 1982; Swanson and Fredriksen, 1982). Several studies have documented the influence of LWD on sediment storage within channels by measuring sediment yield or volume of sediment stored upstream of LWD accumulations before and after experimental removal of LWD from stream channels, or by comparing changes in sediment yield or storage in reaches in which LWD was experimentally removed with that from similar undisturbed reaches (Baker, 1979; Beschta, 1979; Bilby, 1981, 1984; Heede, 1985; Lisle, 1986, 1995; MacDonald and Keller, 1983, 1987).

LWD accumulations can facilitate in-channel sediment deposition and stabilize sediment deposits both upstream and downstream of the accumulation. Channel-spanning logs or debris jams commonly form leaky dams, creating large upstream pools which become relatively long-term sediment storage sites. Unlike either scour pools created downstream of flow obstructions or other sediment storage sites such as riffles and bars, backwater pools upstream of LWD are relatively low-energy (hence, depositional) environments even during high flows, making them more stable sediment storage sites (Thompson, 1995). Many channel-spanning LWD pieces or accumulations are stable for decades or longer (Swanson and Lienkaemper, 1978; Swanson et al., 1984; Hogan, 1987; Lienkaemper and Swanson, 1987). Based on the ages of nurse trees growing on them, the minimum age of LWD jams averaged 50 years in 3rd to 4th-order streams in old-growth forest in Oregon sampled by Gregory (1991), with a maximum age of 150 years.

Smaller or marginal LWD which does not span the entire channel but which is still too large or well-anchored to be moved readily by the stream often anchors bedload deposits (i.e., bars) along the channel margins. In lower gradient streams (which also tend to be larger streams), LWD often anchors downstream as well as upstream sediment accumulations (Keller and Swanson, 1979); the latter typically take the form of marginal bars deposited in eddies downstream of the flow obstruction.

In addition to storing sediment, LWD can also reduce the bedload transport efficiency of a stream (Heede, 1972a, 1972b; Swanson and Lienkaemper, 1978; Beschta, 1979; Bilby, 1981; Megahan, 1982; Nakamura and Swanson, 1993). By dissipating flow energy (Heede, 1975; Marston, 1982) and creating depositional environments that are stable even at relatively high flows (Thompson, 1995), LWD accumulations reduce the likelihood that bed particles will be entrained during competent flows and reduce the mean travel distance of those particles that are entrained, thus reducing sediment transport efficiency.

2.3 Influence of LWD on Magnitude and Frequency of Channel Change

Previous research has shown that LWD can act to either to either a stabilize or destabilize stream channels. Bevan (1948-49) concluded that LWD was responsible for more channel changes than any other agent in the Middle Fork Willamette River in Oregon. Keller and Swanson (1979) argued that debris jams (channel-spanning accumulations of LWD) can locally either accelerate or retard channel bed and bank erosion or deposition and provided a number of examples. Nakamura and Swanson (1993) found that the largest changes in a 10-year record of cross section profiles in a 5^{th}-order stream in the western Oregon Cascade Range were associated with scour and deposition around static old-growth Douglas-fir logs lying in the channel (typically stabilized by rootwads) and old-growth trees which fell into the channel from the stream bank during the period of study. The destabilizing effects of removing LWD from a channel have been well documented by experimental studies (Beschta, 1979; Bilby, 1981, 1984; Heede, 1985; Lisle, 1986; MacDonald and Keller, 1987; Smith et al., 1993a, 1993b; Lisle, 1995), but these studies have typically been short-term in nature and have not addressed the long-term effects of LWD removal on channel stability—i.e., is a channel without LWD, once it has adjusted to that condition, inherently more or less stable than it would be with LWD?

In his review of research on the environmental hydraulics of LWD in streams, Gippel (1995) emphasizes that large pieces of LWD, particularly channel-spanning LWD accumulations, act as large roughness elements that reduce reach-average flow velocity. Such an effect has been documented by MacDonald and Keller (1987), who reported a 250% increase in local flow velocity after removal of a debris jam in Larry Damm Creek (northern California), and by Shields and Smith (1992), who found that reach average flow velocity at low flow in cleared sections of the Obion River (Tennessee) to be approximately 50% greater than in reaches that had not been cleared. Since average boundary shear stress is proportional to the square of mean flow velocity, a small reduction in the latter could translate into a significant reduction in the ability of the stream to erode its bed and banks. However, the effect of LWD on channel roughness and mean flow velocity has been shown by a number of workers to diminish or disappear entirely with increasing discharge in at least some streams (Lisle, 1986; Hecht and Woyshner, 1987; Shields and Smith, 1992). Thus, the channel-stabilizing influence of LWD through its effect on channel roughness and local mean flow velocity may be least significant during large flow events when channel change is most likely to occur, at least in streams where LWD structures are completely submerged during large floods.

If LWD stabilizes the channel, it must by definition reduce the frequency and/or magnitude of channel change. If, on the other hand, LWD de-stabilizes the channel, it should be associated with increased frequency and/or magnitude of channel change. The diverse and sometimes contradictory claims in the literature about the roles of LWD as either a stabilizing or a de-stabilizing influence on channel morphology result in part from the importance of the specific arrangement and structure of LWD in determining its local impact on channel form and process (i.e., all LWD is not functionally equal) and in part from the scale-dependence of the effects of LWD (e.g., the declining effect of LWD on channel roughness and mean flow velocity with increasing discharge). Several authors explicitly address the issue of the spatial scale dependence of LWD function in stream channels (e.g., Keller and Swanson, 1979; Marston, 1982; Nakamura and Swanson, 1993; Gippel, 1995). These studies suggest that the role of LWD changes from that of a static structural channel element with a spatial distribution controlled by input processes in low-order headwater streams to an increasingly dynamic and fluvially controlled element as stream order increases. However, few, if any, studies have directly addressed the question of whether LWD affects channel stability in terms of changing the temporal frequency or pattern of channel change.

Adenlof and Wohl (1994, p. 83) argue that "woody debris both traps sediment and increases form roughness, thus contributing to channel stability." Similarly, in his study of the effects of experimental woody debris removal on a channel impacted by the 1980 eruption of Mt. St. Helens, Washington, Lisle (1995, p. 1808) concluded that "during large-scale, severe disturbances, LWD can diversify hydraulic forces and maintain structural integrity, thereby counteracting the tendency for large sediment inputs to inundate and simplify aquatic ecosystems." Gippel (1995) also emphasizes the role of LWD in providing a varied flow environment and reducing mean flow velocity. By increasing the spatial variability in local hydraulic conditions within the channel, LWD may increase the local variability of channel response to major floods. But at the reach scale, the ability of LWD to reduce mean flow velocity should act to stabilize the channel bed and banks during peak discharges, at least in channels where LWD elements are large relative to the bankfull channel cross section.

3 Study Site and Methods

3.1 Study Site

The Mack Creek study site lies at an elevation of approximately 750 m within the H.J. Andrews Experimental Forest (Andrews Forest) (Figure 3.1). Mack Creek is a 3rd-order watershed with a drainage area of approximately 5.8 km^2 at the gaging station located about 1 km upstream of the junction with Lookout Creek. Since the late 1970s, the lower portion of Mack Creek has been the site of intensive, long-term studies focusing on riparian forest dynamics and the fate and functions of LWD in fluvial systems (e.g., Swanson et al., 1976; Swanson and Lienkaemper, 1978; Swanson et al., 1982a, 1982b; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993, 1994).

This study capitalizes on some of that long-term monitoring data, including two sets of permanent reference channel cross sections in nearly adjacent, contrasting reaches. The upper reach (old-growth site) lies just upstream of the gaging station and a road crossing (Figure 3.2); this reach contains 12 cross sections established in 1978 within an old-growth forest dominated by Douglas-fir with lesser amounts of western hemlock and western redcedar. The lower reach (clearcut site) has 20 cross sections established in 1981 and lies immediately downstream of the gaging station; the hillslopes adjacent to the reach were clearcut in 1964-65, and most of the large woody debris remaining in the channel was flushed downstream by a major flood in December 1964. The distribution of LWD (all pieces >10 cm diameter and >1 m in length) has been monitored over an approximately 1-km stream reach encompassing the two cross section sites since the mid 1980s. The two reaches have approximately the same channel gradient (10.0% for the old-growth reach vs. 9.6% for the clearcut reach) and experience essentially the same discharge; they differ chiefly in the following respects:

1. LWD is abundant in the old-growth reach and largely absent in the clearcut reach (Figure 3.2), and

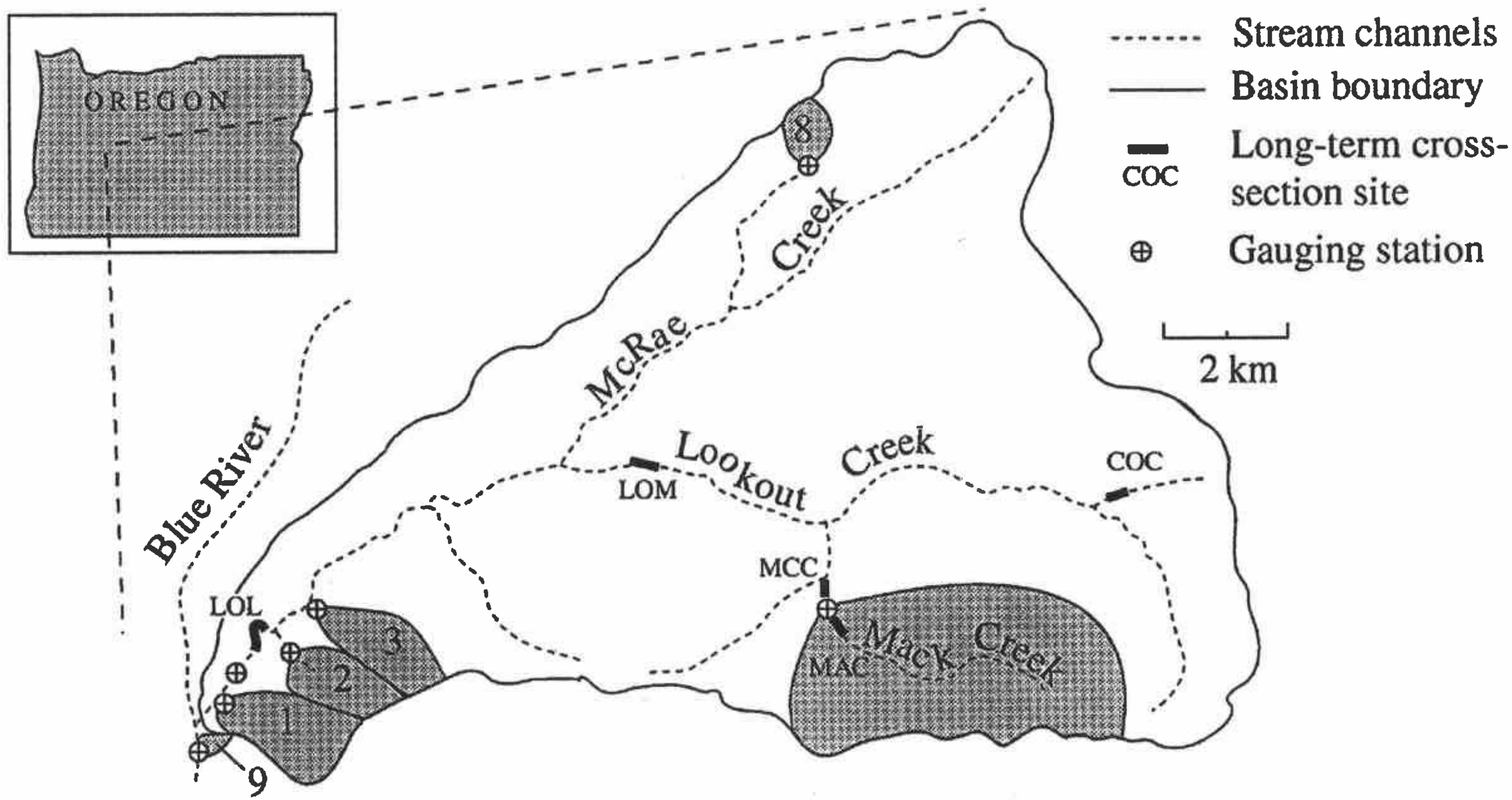


Figure 3.1. Location of long-term cross section monitoring sites, small experimental watersheds, and gaging stations in the Lookout Creek watershed (H.J. Andrews Experimental Forest).

Figure 3.2. Map of Mack Creek old-growth and clearcut cross section sites showing LWD structures, cross section locations, and longitudinal distribution of LWD. Bars at top of lower plot show the number of pieces of LWD >10 m in length located at least partially within the channel, counted in 10-m channel segments. Bottom portion of lower plot shows the estimated volume LWD in 10-m channel segments within each of four zones relative to the channel: *zone 1*– within the low-flow channel; *zone 2*– within the bankfull active channel outside or suspended above the low-flow channel; *zone 3*– suspended above bankfull stage within the bankfull channel width; and *zone 4*– laterally outside the bankfull channel. LWD data from S. V. Gregory (unpublished data).

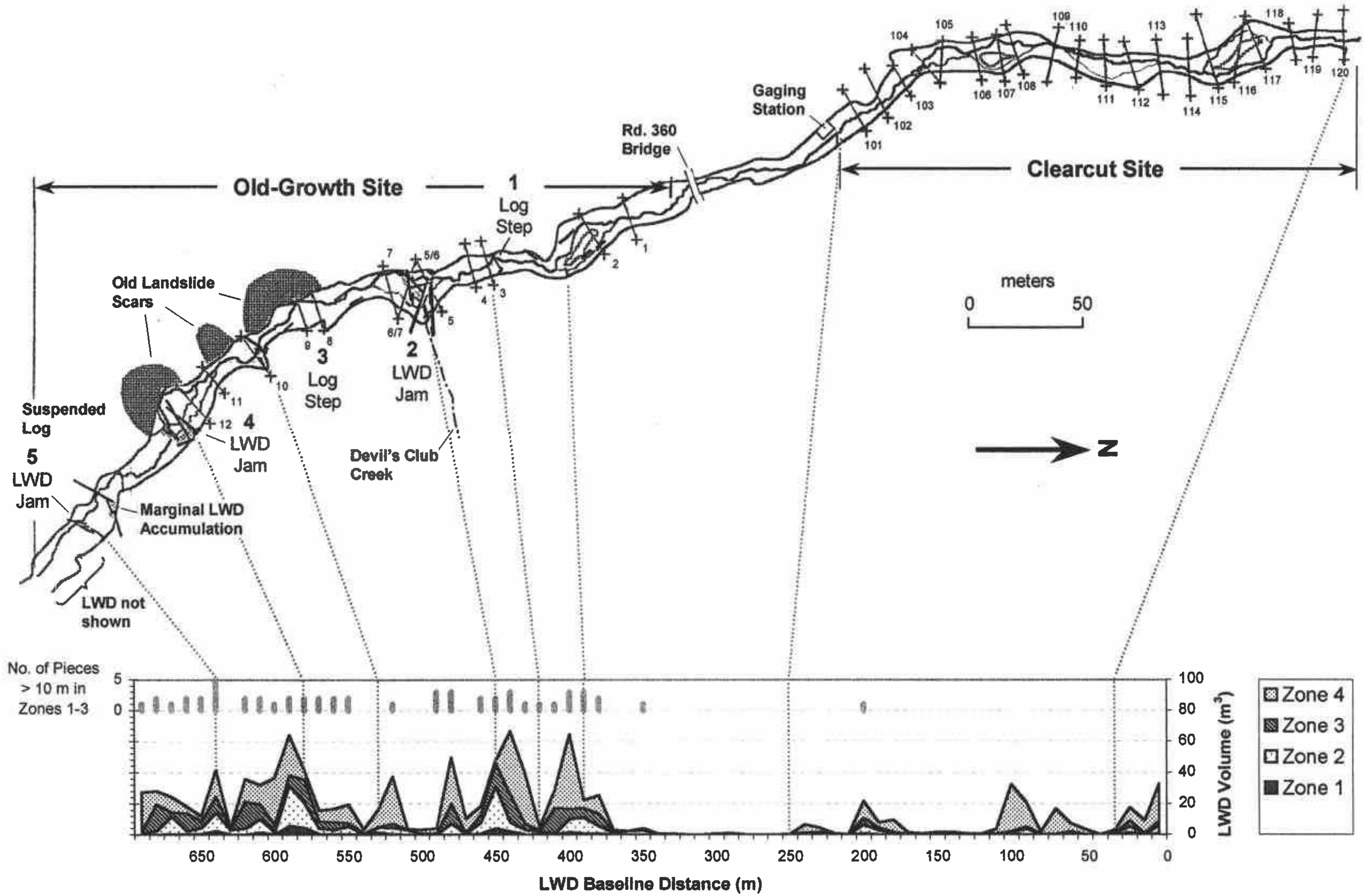

Old-Growth Site
Clearcut Site
1
Log
Step
2
LWD
Jam
3
Log
Step
4
LWD
Jam
5
LWD
Jam
Rd. 360
Bridge
Gaging
Station
Old Landslide
Scars
Suspended
Log
Marginal LWD
Accumulation
LWD not
shown
Devil's Club
Creek
meters
0
50
N
No. of Pieces
> 10 m in
Zones 1-3
LWD Volume (m³)
Zone 4
Zone 3
Zone 2
Zone 1
LWD Baseline Distance (m)

Figure 3.2.

2. the old-growth reach is confined by steep hillslopes in a narrow valley, while the valley floor is wider and the hillslopes generally are not immediately adjacent to the channel in the clearcut reach.

The contrast between the old-growth and clearcut sites is shown clearly in the lower plot of Figure 3.2, based on data provided by S. V. Gregory (unpublished data). The estimated volume of LWD within the channel (zones 1-3; see Section 2.1) averages 0.16 m^3/m (range: 0.00 to 1.08) within the clearcut reach (40-260 m on the LWD baseline [Figure 3.2]) and 1.23 m^3/m (range: 0.05 to 4.6) in the old-growth reach (340-680 m on the LWD baseline). Thus, there is approximately 7.6 times as much in-channel LWD in the old-growth reach as in the clearcut reach. Even more striking is the difference in large LWD pieces capable of forming significant structural elements in the channel. Only a single LWD piece >10 m in length was present within the channel in the clearcut reach in 1996, compared with 51 pieces in the old-growth reach (Figure 3.2); these values are equivalent to frequencies of 0.45 and 15 pieces per 100 m, respectively.

Following Keller and Swanson (1979), LWD is here defined as logs, limbs, and other woody debris that are greater than 10 cm in mean diameter. Fine woody debris or organic debris (OD) refers to woody debris less than 10 cm in diameter. A LWD accumulation is any accumulation of 3 or more LWD pieces and associated OD. Two types of channel-spanning LWD structures are recognized here. A LWD jam is a channel-spanning accumulation consisting of 3 or more key pieces and associated smaller LWD and OD, and sediment which is more than one log diameter in height and which typically anchors a significant upstream sediment accumulation. A log step is a structure roughly one log diameter in height, typically consisting of a single key piece (although it may involve 2 or more pieces that are not vertically stacked and that collectively span the channel) partially or completely buried on the upstream face by accumulated sediment.

Within the old-growth reach, major peaks in LWD abundance generally—but not invariably—correspond to significant LWD structures that affect channel morphology (Figure 3.2). It is important to keep in mind that LWD outside the channel (i.e., in zone 4) cannot directly influence channel morphology, and that LWD within zone 3 (suspended above the bankfull channel) may or may not interact with the channel depending upon how far above the channel it lies and whether it rests on other LWD within the channel. Thus, the large LWD peak at 405 m, which consists principally of LWD in zone 4, is not particularly significant in terms of its potential effect on channel morphology. However, this peak does correspond to an open-framework channel-spanning LWD accumulation that was partly dismantled by the February 1996 flood. Existing channel-spanning LWD jams show up as peaks in LWD volume at 455, 590, and 645 m (Figure 3.2); smaller LWD peaks at 485, 625 and 685 m do not correspond to geomorphically significant structures. On the other hand, single-log steps—which, as will be shown, are significant as channel structures and sediment accumulations sites—do not show up as peaks on the longitudinal plot of LWD density.

3.2 Historical Data Sets

Twelve established reference cross sections in the old-growth site and 20 in the clearcut site (Figure 3.2) have been surveyed on a near-annual basis beginning in 1978 and 1981, respectively. Cross section profiles were surveyed using a builders' auto-level and a telescoping fiberglass stadia rod graduated in 0.5-cm increments. The position of the stadia rod (distance from a permanent reference point on the left bank, viewed in the upstream direction) was measured to the nearest 0.1 m using a fiberglass measuring tape stretched between the permanent cross section end posts. The height of the instrument line-of-sight above the base of the rod was recorded to the nearest 0.01 m. Measurements were taken at 0.5-m intervals along the tape and at slope break points. The substrate at each rod position was also recorded as a 2-letter code. The chief substrate categories (within the active channel) were boulder (>25 cm diameter), cobble (5 to 25 cm), gravel (2 mm to 5 cm), fine sediment (<2 mm; typically sand), log, suspended log, and organic debris (woody debris <10 cm in diameter). Black-and-white photographs of each cross section, typically one upstream and one downstream view, were routinely taken during cross section surveys beginning in 1995.

To assess bed material surface particle size and its variability, modified Wolman (1954) pebble counts were performed at each cross section location beginning with the 1995 survey (Appendix A). Pebble counts consisted of measuring the b-axis diameter of 100 particles selected at random from the streambed within the active channel and within one meter of the cross section line. Particles were selected by traversing the channel along the cross section line and reaching down with one finger while looking away from the streambed to avoid biasing selection. Each particle was measured to the nearest 5 mm (or the nearest 1 mm for particles less than about 5 cm in diameter) using a steel tape measure. Particles less than 2 mm in diameter (i.e., sand) were recorded simply as <2 mm. For large partially buried particles the length of the apparent intermediate axis of the exposed portion of the particle was measured.

Tagging and tracking of LWD movement in Mack Creek was initiated in 1986 by S. V. Gregory and colleagues (Ashkenas, personal communication). A longitudinal baseline extending approximately 1 km upstream from the downstream end of the clearcut (about 40 m downstream of XS 120, Figure 3.2) was established with permanent reference markers on both streambanks at approximate 20-m intervals. Each piece of woody debris greater than 10 cm in diameter and 1 m in length was labeled in the middle and both ends using metal or plastic tags bearing a unique ID number. The longitudinal position of each piece is tracked by assigning the piece to a 10-m channel section corresponding to the upstream or downstream half one of the 20-m baseline segments between permanent reference markers. In addition to LWD lying in or overhanging the channel, pieces lying on the bank or floodplain are included if they are judged to be close enough to the channel to interact with extreme floods. The LWD inventory is updated each year, and data on piece size, location, and condition are recorded for each newly tagged piece and all pieces determined to have moved since the previous year.

3.3 Additional Data Acquisition

Additional field data were collected during the summer of 1997 to more completely characterize channel morphology within the study reaches. Field work included surveying the positions of the cross section endpoint stakes, surveying a high-resolution longitudinal profile of the channel thalweg, mapping the margins of the active channel floodway, and counting the frequency of large boulders (>1-m diameter) within the active channel floodway. The locations of large logs and woody debris accumulations was also mapped within the old-growth reach.

3.3.1 Cross section Endpoint Survey

Although the cross sections have been re-surveyed regularly since they were first established in the 1978 (old-growth site) and 1981 (clearcut site), the locations of the cross section end posts had not been previously mapped or surveyed. Therefore, in order to establish the spatial relationship of the cross sections to one another, the reference post locations were surveyed during the summer of 1997 (Figure 3.2). First, the relative elevations of the cross section reference posts (measured at the ground surface) were surveyed using a builders' auto-level. Subsequently, both the map position and relative elevation of each end post were surveyed using a laser theodolite consisting of a tripod-mounted laser range-finder with a built-in electronically read clinometer in a housing to which a manual sight-through compass could be mounted. Effective precision of the instrument was approximately 0.2% on the horizontal distance (or about +/- 5 cm in 25 m); vertical precision was within approximately 2 to 3 cm over 25 m horizontal distance. The mounted manual compass was graduated in 0.5-degree increments, and readings were interpolated to the nearest 0.1 degree; readings were typically reproducible to within 0.2 degree, which is equivalent to 9 cm at a distance of 25 m.

3.3.2 Longitudinal Profile Survey

Because high-gradient streams tend to dissipate energy through vertical flow oscillations (e.g., step-pool structures; Grant et al., 1990) rather than the lateral oscillations characteristic of low-gradient streams (e.g., meanders and pool-riffle structures), cross sections at best offer an incomplete characterization of channel morphology in a steep mountain stream such as Mack Creek. Therefore, a high-resolution longitudinal profile was surveyed along the channel thalweg of approximately 1 km of Mack Creek, including both the old-growth and clearcut sites.

The survey was performed using the laser theodolite described above. Points were selected along the main thalweg at intervals of approximately one meter, or a smaller interval where necessary to characterize abrupt changes in channel slope or elevation—e.g., at the crest and base of abrupt steps in the longitudinal profile. This resulted in an average distance of 0.9 m between surveyed points along the longitudinal profile. At points where the flow divided around a mid-channel bar, the profile followed the larger channel (or in some cases both channels). The location of any steps greater than about 30 cm in height was noted in the comment column of the field notes. When traversing pools, it was attempted to include the upstream and downstream endpoints of the pool as well as the deepest point located along the thalweg.

Concurrently with the longitudinal profile survey, the margins of the active channel floodway were surveyed at intervals of approximately 5 to 10 m. The objective of this effort was to generate a map of the channel margin. Channel margin survey points were selected using the following criteria: reasonably well-defined channel boundary, clear line of sight from the instrument, inflection points (to capture bends or changes in channel width), and distance from the last surveyed point.

The longitudinal profile and channel margin survey of the 700-m reach containing the old-growth and clearcut sites was completed between July 23 and August 7, 1997. Subsequently, the longitudinal profile survey was extended an additional 100 m upstream of the uppermost cross section on September 5, 1997 to include more LWD structures in the old-growth portion of the stream channel. The sample point spacing for this upstream extension of the longitudinal profile averaged 1.0 m.

Survey data were entered into a spreadsheet, where the measured compass bearings and horizontal and vertical distances were used to calculate the coordinates (x,y,z) of each point with respect to an arbitrary reference point. The coordinate grid was aligned so that north is oriented in the +y direction and east in the +x direction.

3.3.3 Boulder Frequency

Longitudinal variations in the frequency of large boulders in a channel may be an indicator of spatial variations in fluvial and hillslope processes which shape channel and valley floor morphology (Grant and Swanson, 1995; Lambert, 1997) and may be important in the stabilization of LWD jams (Likens and Bilby, 1982). The number of boulders with an intermediate (b-axis) diameter $\geq$ 1 m within each 20-m channel segment along the LWD baseline was counted for the old-growth and clear- reaches shown in Figure 3.2. In addition to exposed boulders lying in the channel, partially buried boulders were counted if it could be determined with reasonable certainty that they met the size criterion. Boulders embedded in the bank were also counted if they would interact with a bankfull discharge or if they were undercut by the channel.

3.4 Data Analysis

Cross section surveys from 1995 and 1996 (Appendix B) were used to estimate the magnitude of channel scour and fill at each cross section location in response to the flood of February 1996. First, data points corresponding to logs lying on or suspended above the channel bed were filtered out, so that the cross section profiles would represent the configuration of the channel boundary exclusive of LWD. Then a public-domain software package, WinXSPRO (Grant et al., 1986; USDA Forest Service, 1998), was used to calculate the area between cross section profiles from consecutive survey dates to determine the cross sectional area of channel scour and fill

(Figure 3.3). These quantities may be thought of as the net volume per unit channel length of bed material eroded from or deposited within the channel, respectively. From this perspective, each cross section represents a single sample point for channel response in a longitudinal transect of the stream channel.

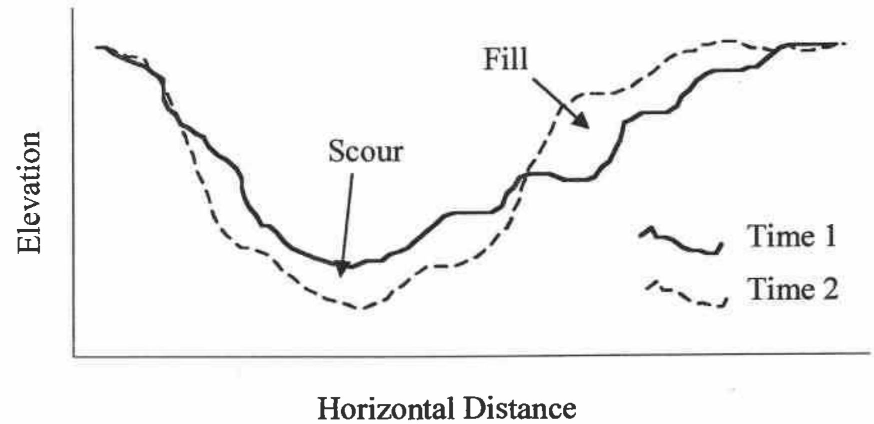


Figure 3.3. Determining cross-sectional area of channel scour and fill using consecutive cross section profile surveys.

The estimates of scour and deposition at each cross section location can be combined to form two other measures of channel response. The *net cross section change* is the algebraic sum of scour (a negative value) and fill (a positive value). A negative value for the net cross section change represents a net loss of bed and/or bank material, or net scour, while a positive value represents a net gain of bed/bank material, or net deposition. The *total cross section change* is the sum of the absolute values of scour and fill, and is a measure of the absolute magnitude of channel response (volume of sediment reworked per unit channel length) at a single cross section. To obtain a measure of channel response at the *reach* scale, the estimates of scour, deposition, net change and total change for all cross sections at a site (i.e., old-growth or clearcut) were averaged to yield a reach-average response.

Bed material particle size data collected in conjunction with cross section surveys during the years 1995-1997 were used for the following purposes:

1. to look for reach-scale differences in the bed surface particle size distribution between the old-growth and clearcut sites,
2. to assess whether the within-reach spatial variability in bed surface particle size differs between the two reaches,
3. to assess whether LWD structures significantly influence bed surface particle size locally within the old-growth reach (e.g., is bed material finer immediately upstream of LWD structures?), and
4. to determine whether the bed surface particle size distribution at the two sites changed in response to the February 1996 flood.

Particle size data were analyzed in two ways. First, the particle size distribution for each sample (one sample at each cross section location) was represented by summary statistics or "representative" particle sizes, in particular the D_{50} (median particle diameter) and the D_{84} (diameter of a particle larger than 84% of the particles in the sample) (Appendix A). Where sample sizes were sufficient (e.g., reach-scale comparisons between sites or between years at either site), differences were tested for significance using a Student's t-test after log-transforming the data (to reduce skew in particle size distribution). A second way the particle size data were analyzed was to combine all the samples from each population being sampled (e.g., old-growth site vs. clearcut site) and compute a cumulative particle size frequency distribution based on the composite samples. The resultant empirical cumulative density functions, or CDFs, were then compared graphically.

4 Results

4.1 Channel Morphology

4.1.1 Channel Width and Planform Pattern

Measurements of channel width in the old-growth and clearcut reaches at Mack Creek are consistent with previously reported findings that reaches having abundant LWD have greater average channel width and variation in channel width than reaches with little LWD (e.g., Zimmerman et al., 1967; Keller and Swanson, 1979; Nakamura and Swanson, 1993). Mean channel width is greater for the old-growth site (13.0 m, n = 17) than for the clearcut site (10.7 m, n = 11), a difference which is marginally statistically significant (1-sided p-value = 0.044; t-test). This difference in width is all the more significant given that the valley floor widens downstream of the road crossing (Figure 3.2); thus, the channel is wider within the old-growth reach even though it is noticeably more constrained by the valley walls.

The old-growth reach is also slightly more variable in width than the clearcut reach, as reflected in its higher coefficient of variation for channel width (3.80 for the old-growth reach vs. 3.25 for the clearcut reach). Variations in channel width are clearly associated with LWD structures (Figure 3.2). Channel width at four of five channel-spanning log steps or LWD jams is greater than the reach average of 13.0 m; the mean width at all 5 locations is 16.7 m, or 28% greater than the reach average (Table 4.1). Channel widths at the two log step locations are close to the reach average (9.5 and 15 m), while widths at the three LWD jam locations average 19.7 m, or 52% greater than the reach average.

Another difference between the old-growth and clearcut reaches, which is apparent in the plan view channel map (Figure 3.2), is that the latter tends to bifurcate frequently, with mid-channel bars separating the main or low-flow channel from a secondary channel which is active only during somewhat higher (wet season) flows. Within the old-growth reach, only a short (~30 m) length of channel near XS 2 has a divided channel. (Flow sometimes splits around gravel deposits on the upstream side

Table 4.1. Channel width variations at Mack Creek old-growth site associated with LWD.

	Channel-spanning LWD	LWD Jams	Log Steps	Entire Reach
Widths (m)	16.5, 20.5, 15, 22, 9.5	16, 20.5, 22	15, 9.5	---
Avg. width (m)	16.7	19.7	12.3	13.0
% difference from reach avg.	+28%	+52%	-5%	---

of LWD jams, and downstream of the lower two LWD jams the channel widens while the thalweg becomes poorly defined, but distinct multiple channels generally do not occur within the old-growth reach.) This difference may be due to differences in riparian vegetation: dense willow thickets stabilize mid-channel bars in the clearcut reach but are absent from the old-growth reach.

4.1.2 Longitudinal Profile

The longitudinal profile reveals significant differences in the structure of the channel between the old-growth and clearcut reaches (Figure 4.1). Significant inflections in the longitudinal profile are associated with each of the five channel-spanning LWD structures labeled in Figure 3.2. Overall, approximately 30% of the total elevation loss in the longitudinal profile within the old-growth reach is associated with these LWD structures. None of the elevation loss in the profile is associated with LWD within the clearcut reach.

LWD-caused steps in the longitudinal profile of the old-growth reach are significantly larger than most boulder-related steps in either reach. A few large boulder steps in the clearcut reach (e.g., at XS 106 and 107, Figure 4.1) have a height of 1 m or more, rivaling the log steps (LWD structures 1 and 3, Figure 4.1), but the boulder steps do not create the 20- to 40-m long segments of low-gradient channel that are found upstream of the LWD structures. The two log steps have heights of about 1

Figure 4.1. Longitudinal profile for the portion of Mack Creek shown in Figure 3.2. The longitudinal distance is based on an 11-point moving average of the *x*- and *y*-coordinates of the surveyed points along the channel thalweg, but the vertical coordinate has not been smoothed. The upper row of labels for the horizontal (longitudinal distance) axis apply to the upper plot (old-growth reach), while the lower row of labels apply to the lower plot (clearcut reach). Numbered features correspond to numbered LWD structures in Figure 3.2.

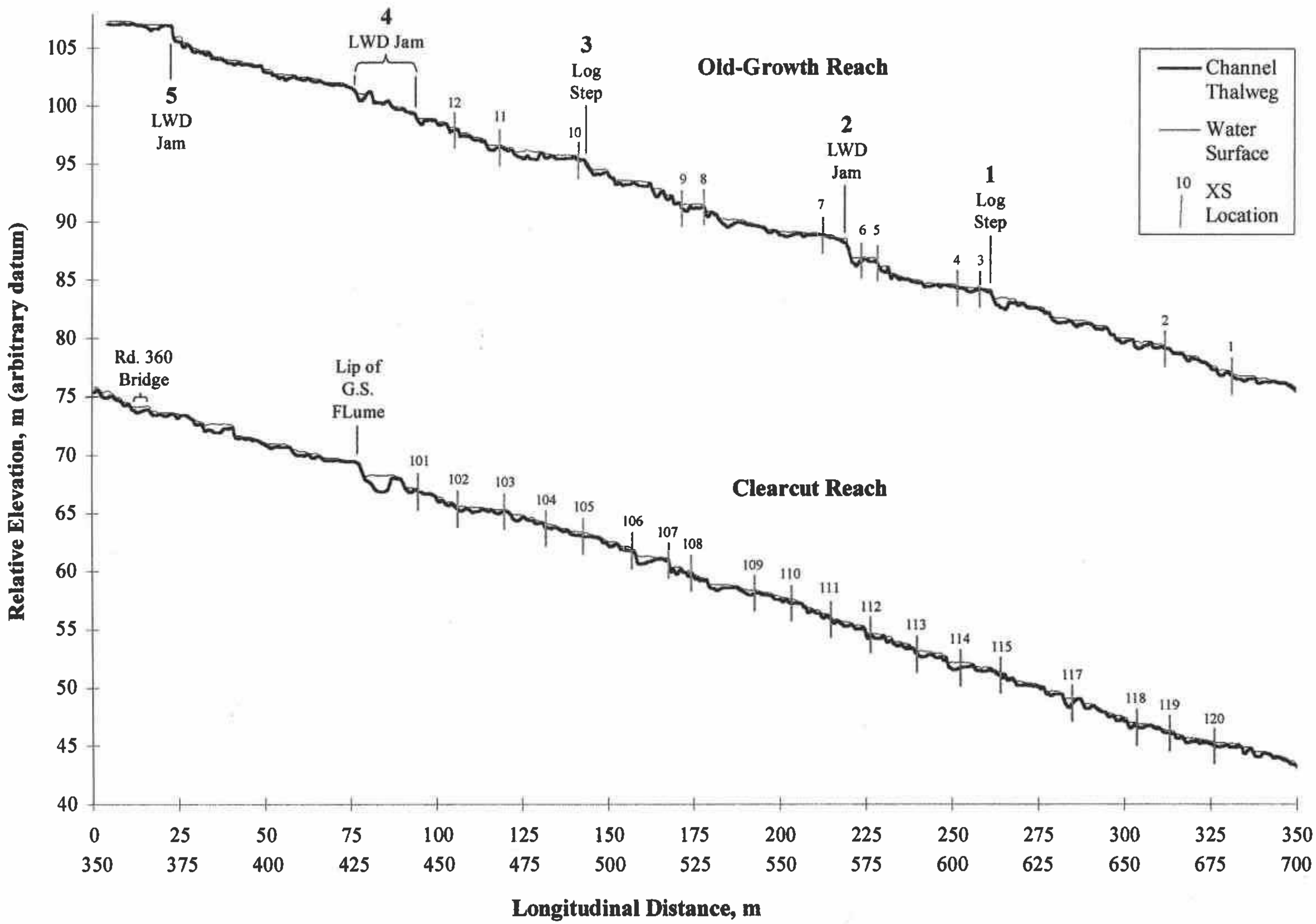


Figure 4.1. (continued)

to 1.5 m each (Figure 4.2), while the LWD jams produce steps about 2 to 2.5 m in height (Figure 4.3).

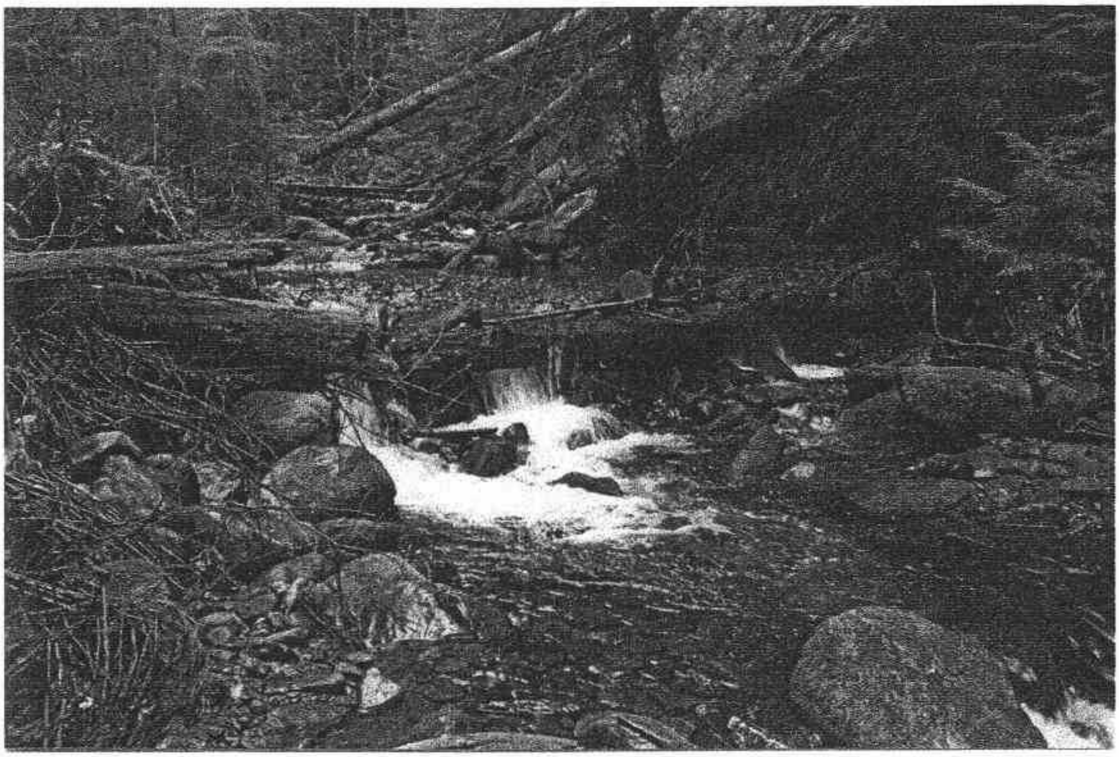


Figure 4.2. Log step at the Mack Creek old-growth (MAC) site. Cross section 10 crosses the channel just upstream of the step. Note the fine gravel deposit upstream of the step. Orange disc is 30 cm (1 ft) in diameter; step height is just over 1 m.

The middle LWD jam (LWD structure 4) does not show up as a step in the longitudinal profile (Figure 4.1) because the thalweg (and most of the flow, even at high discharge) cuts diagonally through the jam and around the end of one of the key logs (Figure 3.2), descending over a series of boulder steps within the jam and lengthening the distance over which the drop occurs (Figure 4.4). The jam does correspond a convex inflection point in the longitudinal profile, however, with at least 25 to 30 m of low-gradient channel upstream.

The differences in the structure of the longitudinal profile between the old-growth and clearcut reaches are revealed more clearly in the smoothed, de-trended longitudinal profile (lower plots in Figures 4.5 [a] and [b]). A positive slope on the

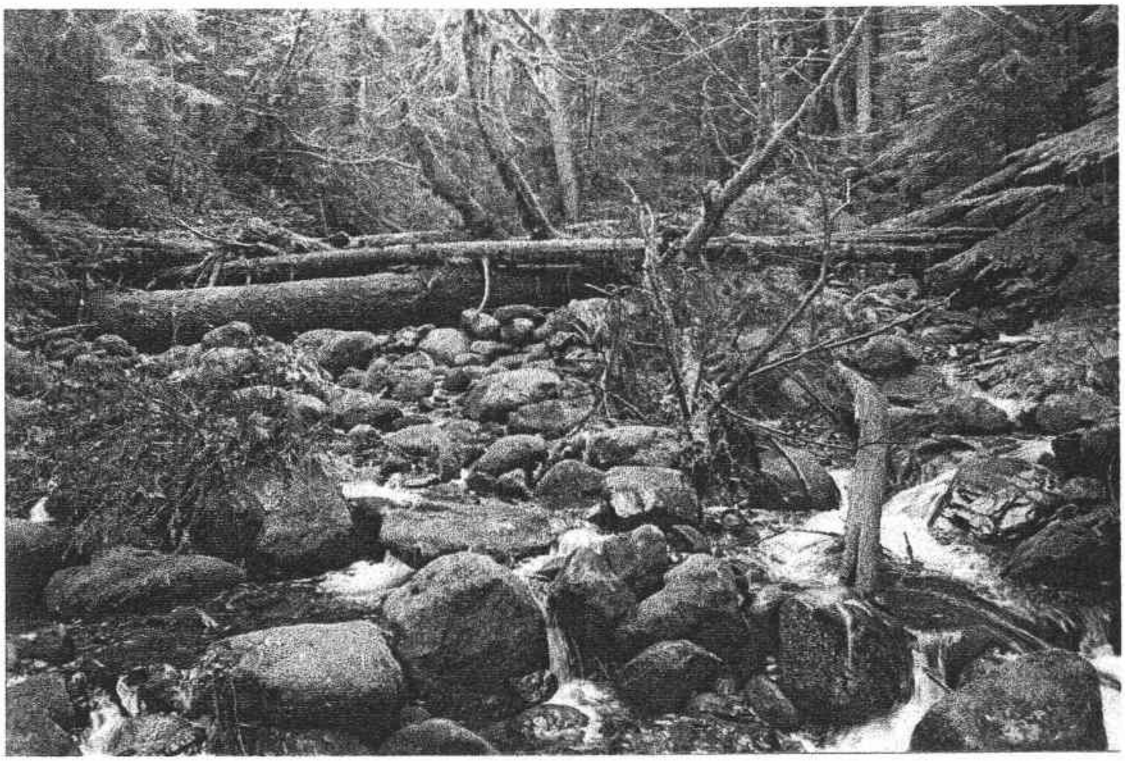


Figure 4.3. View of channel at Mack Creek old-growth (MAC) site showing armored channel bed downstream of a large LWD jam. Vertical distance between water surface immediately up- and downstream of the jam is approximately 1.5 m; total height of the structure is a little over 2 m.

residual plots (i.e., where the residual increases in the downstream direction) indicates a section of channel with below-average slope, while a negative slope indicates a channel section with above-average slope. Peaks in the residual plot correspond to inflection points between channel segments with below-reach-average and above-reach-average slope. Major peaks in longitudinal profile residual plot for the old-growth reach correspond to significant LWD structures (Figure 4.5[a]), while peaks in the clearcut reach, where LWD structures are absent, are smaller and less well-defined (Figure 4.5[b]).

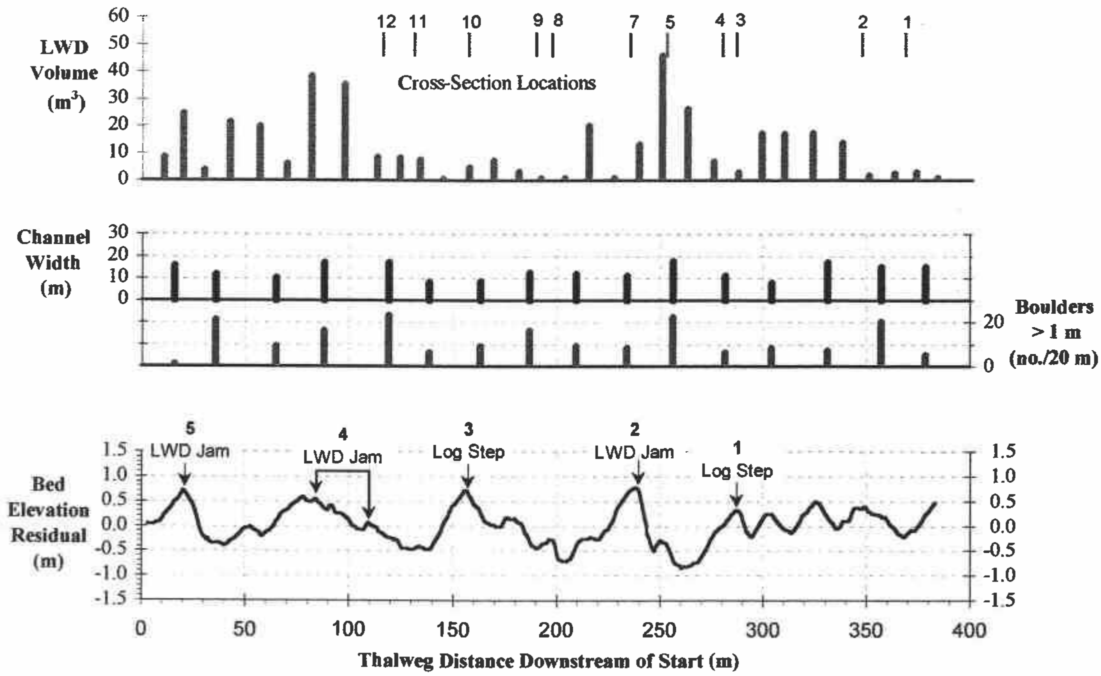
As suggested above, an important effect of large LWD on the channel is that it alters the frequency distribution of channel gradient along the longitudinal profile. Figures 4.6 (a) and (b) show the frequency distribution for the low-flow water surface gradient for the old-growth and clearcut reaches, respectively, calculated over a 10-m

Figure 4.4. View of channel within LWD jam (structure no. 4 in Figure 3.2). Flow is diverted down a boulder cascade and against the left bank, which consists of exposed bedrock. Note the gravel in the foreground, which is typical of sediment stored upstream of LWD jams in Mack Creek, but is relatively uncommon elsewhere in the channel.

interval centered on each point in a 5-point moving average of the longitudinal profile in Figure 4.1. The histograms reveal that the frequency distribution for local channel slope at the old-growth site is skewed toward low slopes, while local channel slope at the clearcut site is essentially normally distributed. The cumulative distribution curve for the local channel slope at the old-growth site (Figure 4.6[a]) has a flatter slope than the curve for the clearcut site (Figure 4.6[b]). This implies that the old-growth site has a more uniform distribution of local channel slopes, with less of the channel having slope close to the average value of 9.3% and more of the channel having significantly greater or lesser slope. Based on a 10-m moving average of the longitudinal profile (Figure 4.1), 36.9% of the channel in the old-growth reach had a local slope of ≤7%, vs. 20.4% of the channel within the clearcut reach, while 23.3% of the old-growth channel vs. 7.5% of the clearcut channel had a slope of ≤5%. Thus, the proportion of

Figure 4.5. Longitudinal plot showing quantity of LWD and channel characteristics at Mack Creek: (a) old-growth site; (b) clearcut site. For each site, the top plot shows the estimated volume of LWD within or suspended above the channel within each 10-m channel segment; the second pair of plots show a count of boulders with b-axis diameter >1 m within 20-m channel segments and the channel width at the midpoint of each segment; and the bottom plot shows the residual from a linear regression of bed (thalweg) elevation vs. distance. The bed elevation residual plot has been smoothed by applying a 9-point moving average to filter out high frequency oscillations.

(a) Old-Growth (MAC) Site



(b) Clearcut (MCC) Site

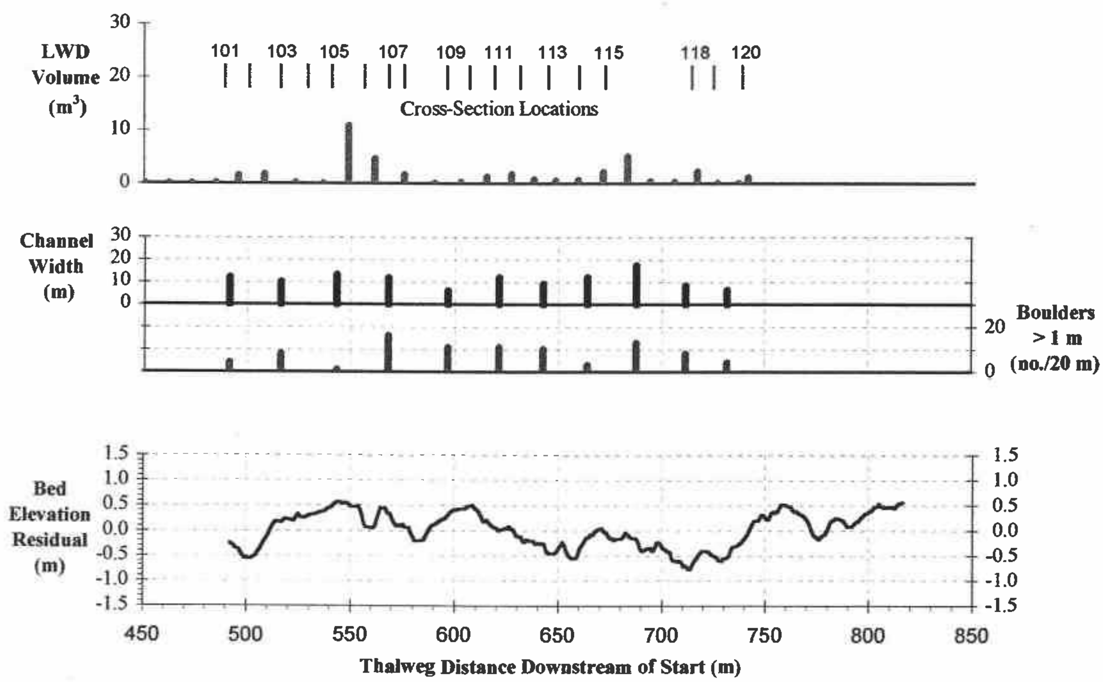
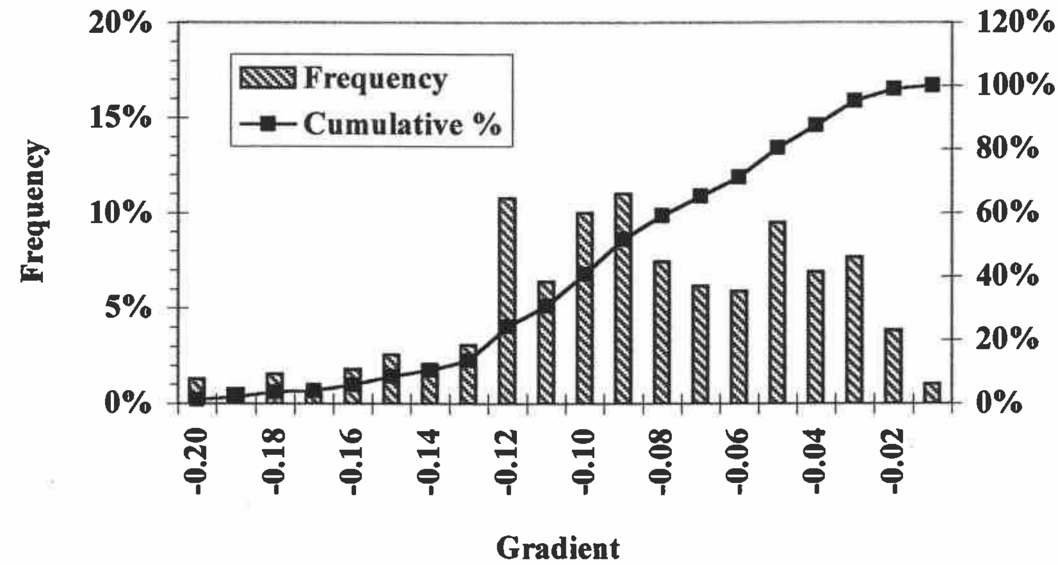


Figure 4.5 (continued)

(a) Old Growth (MAC) Site



(b) Clearcut (MCC) Site

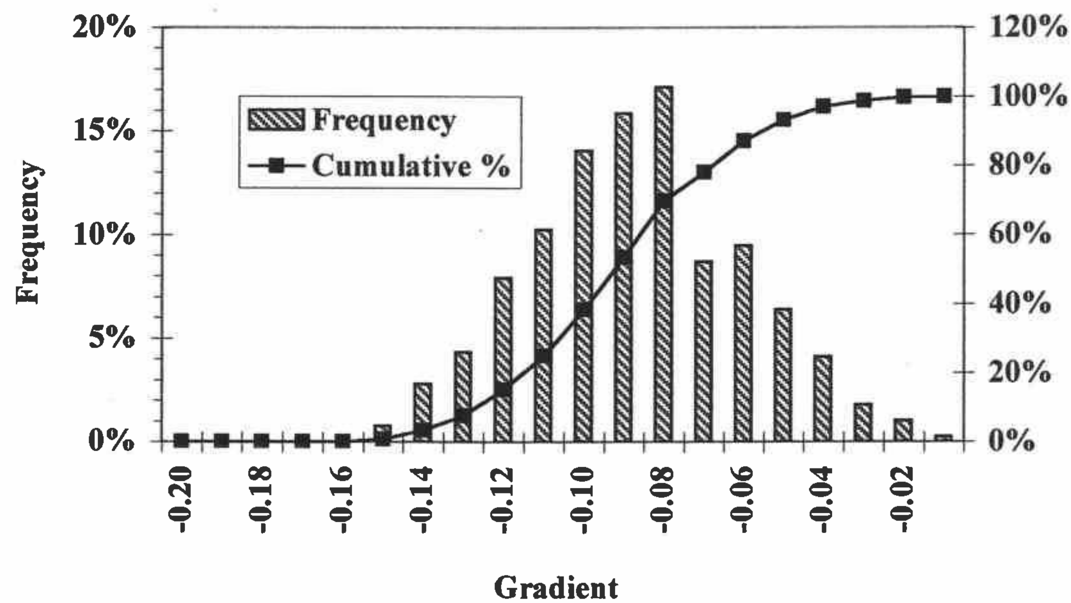


Figure 4.6. Frequency distribution for the local low-flow water surface gradient in Mack Creek: (a) old-growth (MAC) site; (b) clearcut (MCC) site. Water surface slope was calculated over a 10-m interval centered on each point in a 5-point moving average of the longitudinal profile in Figure 4.1.

the channel in the old-growth reach with a bed slope of 5% or less was three times as great as in the clearcut reach.

There is a rather striking spatial correlation between the frequency of large boulders (>1 m b-axis diameter) and the LWD jams (Figure 4.5). Three of the four 20-m LWD baseline channel segments with boulder counts of 20 or more (i.e., ≥1 boulder per meter of channel length) are located immediately downstream of LWD jams (structures 2, 4 and 5; Figure 4.5[b]); the fourth is located just downstream of a former LWD accumulation just upstream of XS 2 that was partially dismantled by the February 1996 flood. Channel widths are also greater where the boulder counts are highest, suggesting that the greater boulder frequency may, in part, simply reflect greater streambed surface area. But other evidence suggests that increased channel width alone does not explain the pattern of variation in boulder frequency. For example, large boulders were much less abundant upstream than downstream of the uppermost LWD jam (structure 5 in Figure 4.5[a]), even though channel width was slightly greater upstream than downstream of the jam. Also, while conducting the boulder count, it was observed that exposed boulders meeting the size criterion were clearly clustered at the base of LWD structures and immediately downstream.

4.2 Channel Response to Flood of February 1996

4.2.1 Cross Section Response

Cross section and particle size data for 1995-1997 reveal different responses to the February 1996 flood in the old-growth and clearcut reaches. In general, the dominant channel responses revealed by the cross sections and particle count data in the clearcut reach were scour and an associated increase in bed surface particle size, while the most pronounced changes in the old-growth reach were associated with aggradation upstream of LWD.

Of the 18 cross sections in the clearcut reach for which magnitude of change could be determined, 8 exhibited substantial scour (XS 101, 102, 107, 108, and 115) or moderate scour (XS 111, 112, and 114) as a result of the February 1996 flood (Table

Table 4.2. Summary of channel responses to the flood of February 1996 at the Mack Creek cross section locations.

Cross-Section No.	Cross-Section Response [1]		Textural Response
	total response	net response	
Old-Growth Site			
1	mod. scour	minor scour	coarsened
2	major scour	mod. scour	coarsened
3	major fill	major fill	fined
4	minor scour	no significant change	no change
5	minor scour	minor scour	fined
6	unclear	unclear	coarsened
7	major fill + minor scour	major fill	improved sorting
8	no significant change	no significant change	no change
9	minor scour	minor scour	coarsened
10	major fill	major fill	fined
11	mod. scour	minor scour	no change
12	minor scour	no significant change	coarsened
Clear-Cut Site			
101	major scour	major scour	coarsened
102	major scour	major scour	no change
103	minor fill	minor fill	no change
104	minor scour + minor fill	no significant change	coarsened
105	mod. fill	minor fill	coarsened
106	minor fill	no significant change	coarsened
107	major scour	mod. scour	coarsened
108	major scour	mod. scour	coarsened
109	minor scour	minor scour	coarsened
110	mod. fill	minor fill	coarsened
111	mod. scour	mod. scour	coarsened
112	mod. scour	mod. scour	coarsened
113	minor scour	minor scour	coarsened
114	mod. scour	mod. scour	coarsened
115	major scour	major scour	no data
117	no data	no data	coarsened
118	minor scour + minor fill	no significant change	coarsened
119	no significant change	no significant change	no change
120	minor scour	minor scour	coarsened

[1] "No significant change" indicates an estimated cross-sectional area of scour or fill of less than 1 m^2. "Minor" indicates changes > 1 m^2; "moderate", >2 m^2; and "major", >3 m^2. "Total response" includes scour and/or fill, if signficant; "net response" is the difference between scour and fill.

4.2). Three cross sections (XS 109, 113 and 120) exhibited minor scour, while two others (XS 104 and 118) experienced both minor scour and minor fill for no significant net change. Only one cross section (XS 119) showed no evidence of significant scour or fill. Four cross sections exhibited moderate (XS 105, 110) or minor (XS 103, 106) fill.

Channel scour within the clearcut reach was not uniformly distributed, but occurred in two distinct zones (Figure 4.7[b]). The upper scour zone extended at least 25 to 30 m downstream from the concrete flume for the gaging station (Figure 3.2), where XS 101 and 102 both experienced major scour and a transition from alluvial channel in 1995 (predominantly cobble with no exposed bedrock) to a channel underlain by bedrock under most of its low-flow wetted perimeter in 1996. No bedrock is exposed below a few meters downstream of XS 102. Channel scour in this zone (especially XS 101) may be influenced by the presence of the gaging station flume, which creates the deepest pool (immediately downstream of the flume, Figure 4.1) in the 800 m of surveyed channel.

Immediately downstream of the upper scour zone, a zone of minor net deposition to no net change extends from XS 103 to XS 106, a distance of approximately 40 m (Figure 4.7[b]; Table 4.2). A second and longer zone of channel scour extends for at least 100 m between XS 107 and 115 (Figure 4.7[b]; Table 4.2). One cross section within this zone (XS 110) exhibited minor net fill, but 5 of the 7 other cross sections in this sub-reach exhibited moderate to major scour and the remaining 2 exhibited minor scour. It is difficult to say whether this scour zone extended farther downstream than XS 115, since XS 116 was abandoned after 1990 and the location of one end of XS 117 appears to have been moved in 1996 (field notes give no indication of a post being replaced), but XS 118 (about 40 m downstream of XS 115) and XS 119 exhibited no significant net change (Table 4.2). Cross section 120 showed minor net scour.

In general, the old-growth cross sections revealed a pattern of substantial aggradation upstream of channel-spanning LWD structures and minor to moderate scour downstream of and between these structures. All three cross sections immediately upstream of channel-spanning LWD within this reach (XS 3, 7 and 10)

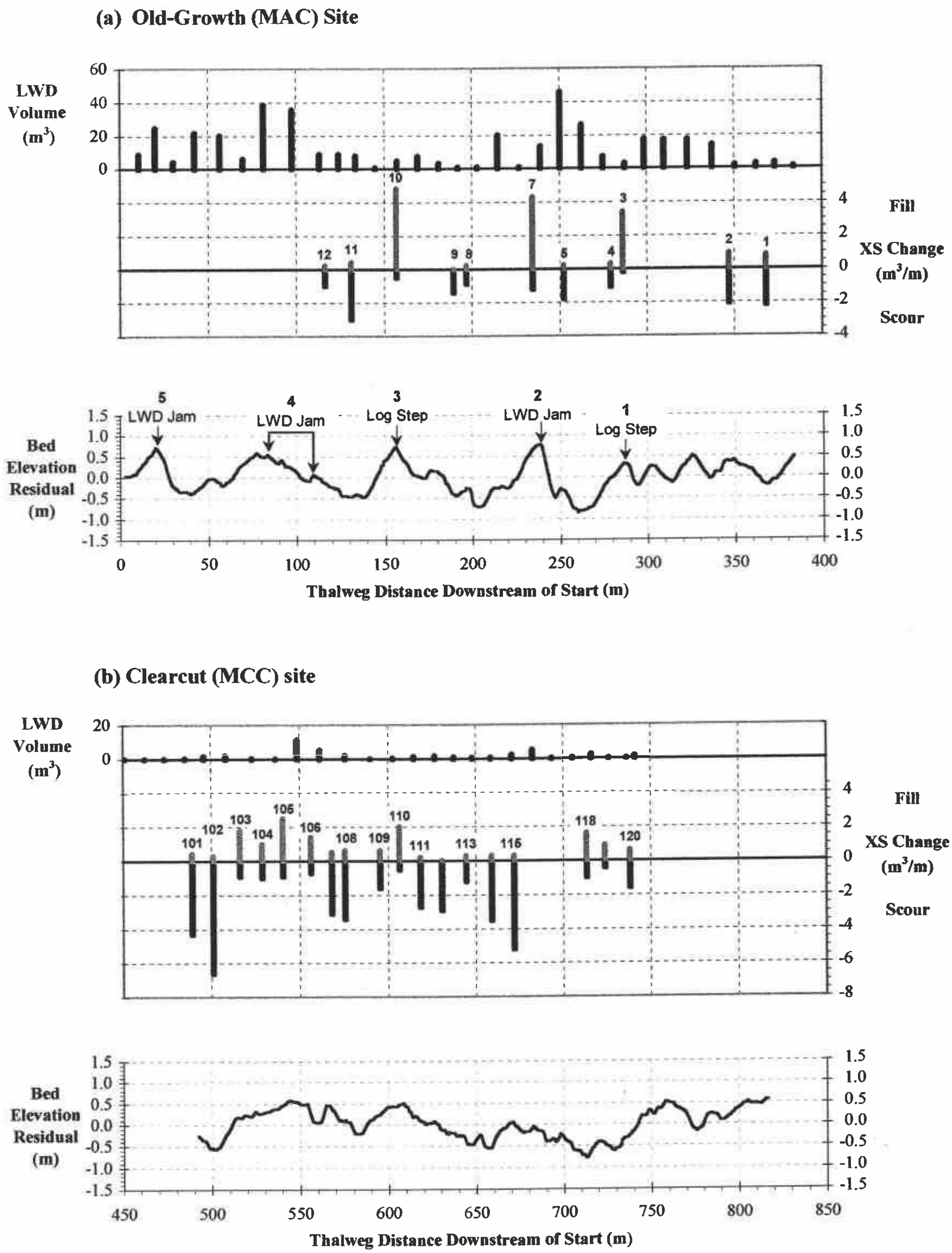


Figure 4.7. Longitudinal plot showing volume of in-channel LWD, cross section scour and fill, and bed elevation residual for the Mack Creek cross section sites: (a) old-growth site; (b) clearcut site.

exhibited substantial aggradation in response to the February 1996 flood (XS 7 also exhibited minor scour), while three other cross sections not closely associated with existing LWD structures (XS 1, 2 and 11) experienced moderate to major scour. Five of the six remaining cross sections exhibited minor scour (XS 4, 5, 9, and 12) or no significant change (XS 8). (Scour and fill volumes could not be calculated for XS 6, which crosses the lower LWD jam in the old-growth reach at a diagonal (Figure 3.2), because the position of a significant fraction of the channel bottom could not be determined in 1995 due to the presence of a suspended log parallel to the cross section line.)

Aggradation at XS 3 and 7 was the result of deposition upstream of existing structures, but aggradation at XS 10 resulted from accumulation of sediment behind a single channel-spanning log that was deposited immediately downstream of XS 10 during the February 1996 flood (Figures 3.2, 4.2). According to the LWD database, this log (#O403) moved from a position anchored on the bank and oriented parallel to the channel (completely outside the low-flow channel but wholly within the bankfull channel and 50% above bankfull stage) to a new position a few meters downstream perpendicular to and spanning the channel, 80% within the low-flow channel and 100% below bankfull stage.

At the reach scale, based on average cross section responses, old-growth and clearcut sites exhibited essentially the same overall magnitude of total scour and fill, but substantially different degrees of *net* channel change (Figure 4.8). The old-growth site exhibited nearly identical amounts of scour and fill overall, resulting in negligible net erosion or deposition within this reach, while cross sections at the clearcut site experienced more scour and less fill, with the net result that substantial net scour occurred within this reach (Figure 4.8). Due to the large variability of the individual cross section responses, these differences are not statistically significant, but the differences in scour and net change are nearly so at a significance level of 0.05 (note 95% confidence intervals in Figure 4.8).

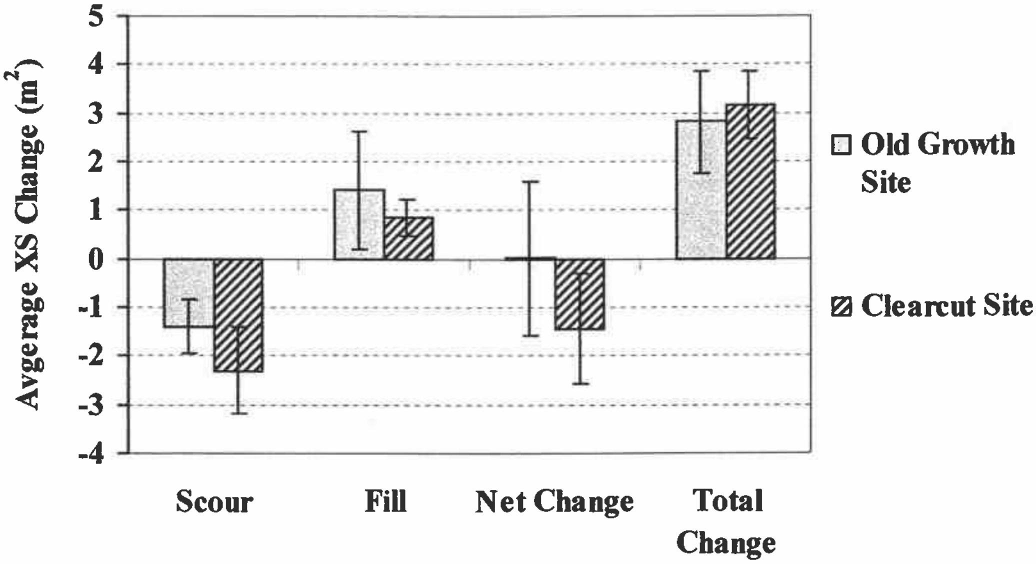


Figure 4.8. Comparison of average 1995-96 cross section changes at the Mack Creek old-growth and clearcut sites. Error bars show 95% confidence interval.

4.2.2 Cross Section Response in Relation to Inputs or Movement of LWD

Because LWD has been widely reported to be an important mechanism for sediment storage in mountain streams (Megahan and Nowlin, 1976; Megahan, 1982; Nakamura and Swanson, 1993; Thompson, 1995), it was hypothesized that increases in in-channel LWD would tend to be associated with channel aggradation or fill, while decreases in LWD in the channel would tend to be associated with channel scour. More crudely, it was hypothesized that larger cross section changes would be associated with locations where there was significant movement or new inputs of LWD than locations where LWD changes were absent. However, the data do not strongly support either hypothesis. Changes in distribution of LWD volume within the channel (zones 1 to 3) between 1995 and 1996 were not spatially correlated with cross section changes for the same period (Figure 4.9 [a]). Neither the direction of cross section change (i.e., scour vs. fill) nor its magnitude bore any consistent relationship to changes in LWD volume in the channel in the immediate vicinity of the cross section. Of the cross sections that experienced the greatest scour (XS 1, 2, and 11) or fill (XS 3, 7 and 10), only two (XS 2 and 7) were proximal to large changes in

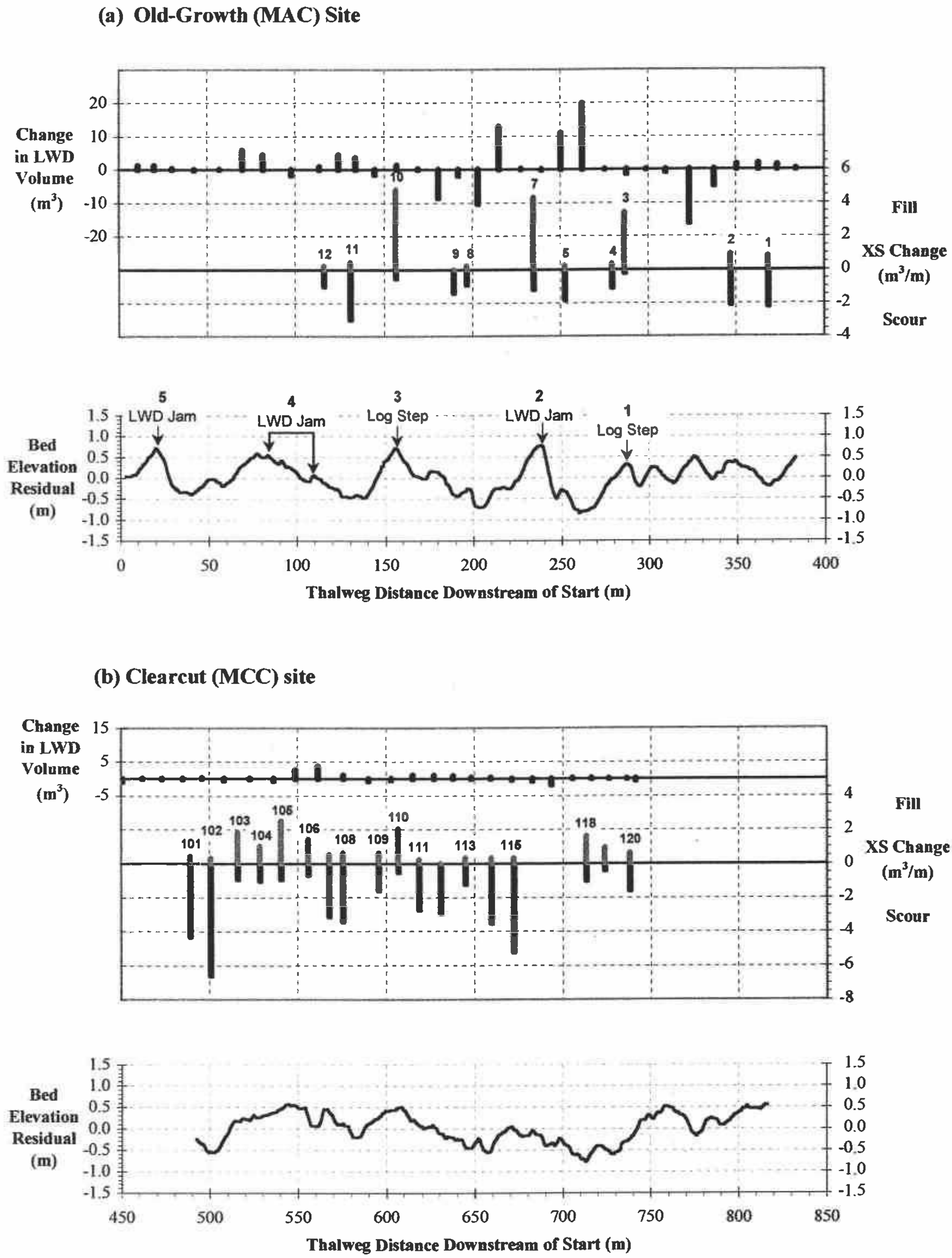


Figure 4.9. Longitudinal plot showing 1995-96 change in volume of in-channel LWD, cross section scour and fill, and bed elevation residual for the Mack Creek cross section sites: (a) old-growth site; (b) clearcut site.

LWD volume within the channel (Figure 4.9 [a]). Partial dismantling of a channel-spanning LWD accumulation at the head of a mid-channel bar just upstream of XS 2 in the 1996 flood may have contributed to scour at XS 2, while accumulation of additional LWD by the LWD jam immediately downstream of XS 7 may have contributed to aggradation at XS 7. (Scour at XS 1 may be related to a removal of a 10-ft diameter culvert 30 m downstream of in September 1994 to improve fish passage and prevent mass failure of the road fill [Gregory, personal communication]. Approximately 1200 to 1500 cubic yards of sediment were excavated from the channel at that time [Cissel, personal communication].) In the clearcut reach, there was little LWD in the channel to start with and hence little redistribution of LWD volume. Thus, channel changes in the clearcut reach clearly were not driven by redistribution or new inputs of LWD (Figure 4.9 [b]).

The longitudinal pattern of channel slope as revealed by thalweg elevation residual appears to be a much better predictor of cross section change than either the LWD volume in the channel or the change in LWD volume in the channel before and after the flood (Figures 4.7, 4.9). Channel scour in 1996 was observed principally at locations where channel gradient is greater than the reach average (XS 5, 8, 9 and 12 in the old-growth and 101, 107, 108 and 111-113 in the clearcut) or at concave-upward inflection points in the longitudinal profile where channel slope decreases abruptly (old-growth XS 1 and 11 and clearcut XS 102 and 114). Channel fill was observed at convex-upward inflection points in the longitudinal profile (sections 3, 7, 10, 106, and 110) and where channel gradient was less than the reach average (sections 103-105). Exceptions to this pattern were XS 2 and 115, both of which are located at convex-upward inflection points yet experienced scour rather than aggradation.

4.2.3 Particle Size Response

The old-growth and clearcut reaches exhibited strikingly different bed material texture responses to the February 1996 flood, both at the reach and within-reach scales. At the reach scale, the old-growth reach exhibited negligible change in its bed

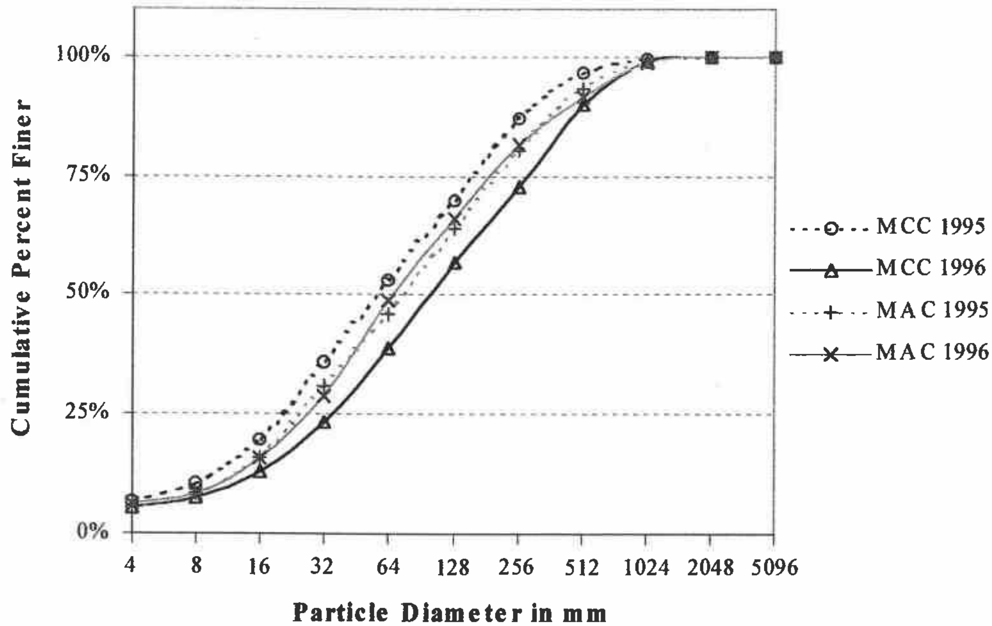


Figure 4.10. Cumulative particle size distribution for the Mack Creek old-growth (MAC) and clearcut (MCC) sites for 1995 and 1996. Plots were created using pooled data from all cross sections at each site.

surface particle size distribution, while the clearcut reach exhibited pronounced coarsening (Figure 4.10). This coarsening in the clearcut reach was significant for all size fractions (Table 4.3), and was more consistent and uniformly distributed than the cross section response within the reach (Table 4.2). Nearly all the cross sections within the clearcut reach exhibited a discernible increase in particle size, and none exhibited a decrease in particle size. In contrast, cross sections in the old-growth reach exhibited a mix of coarsening and fining, with most of the latter occurring upstream of LWD structures (XS 3 and 10; Table 4.2).

At the reach scale, differences in bed surface particle size distribution between the old-growth and clearcut sites were greater after the February 1996 flood than they were prior to this flood. The cumulative distribution curve for both sites had a similar shape in both 1995 and 1996, indicating roughly the same degree of sorting, but the clearcut site had somewhat finer bed surface than the old-growth site in 1995 and a coarser distribution in 1996 (Figure 4.10). The differences between the two sites in the average median (D_{50}) and D_{84} particle size at the cross section locations were not

Table 4.3. Selected 1995 and 1996 particle size statistics (in millimeters) for the old-growth and clearcut sites. Indicated p-values for between-year comparisons are from a paired t-test, using log-transormed data, of the hypothesis that the mean difference between 1995 and 1996 values is zero, with the alternative hypothesis that the difference is nonzero; values of 0.05 or less are shown in **boldface.** The p-values in the bottom row of the table are from a two-sample t-test, also using log-transformed data, for a difference between sites in a given year.

Site	Parameter	n	D_{84} 1995	D_{84} 1996	D_{50} 1995	D_{50} 1996	D_{16} 1995	D_{16} 1996
MCC	mean	17	224	396	60.9	95.0	14.5	20.4
	95% C.I.		186-269	363-432	49.7-74.7	83.2-108	12.2-17.2	17.3-24.0
	p-value		**<0.0001**		**0.0026**		**0.0136**	
MAC	mean	11	280	273	80.9	68.9	19.3	19.1
	95% C.I.		198-394	179-414	57.4-114	48.2-98.6	14.2-26.4	14.3-25.5
	p-value		0.8821		0.3136		0.9163	
MCC vs. MAC	p-values		0.1454	**0.0195**	0.0864	**0.0325**	**0.0476**	0.6073

statistically significant in 1995 (2-sided p-value of >0.05), but *were* significantly different in 1996 (Table 4.3, bottom row). The average D_{16} value based on the individual cross section samples was not significantly different between the sites in 1996, but was significantly different in 1995 (*greater* in the old-growth reach than in the clearcut reach). (Note that Figure 4.10 and Table 4.3 show somewhat different D_i values because Figure 4.10 is based on a composite sample of all cross sections at a site, while Table 4.3 counts each cross section as a separate sample to maintain enough degrees of freedom to permit statistical testing).

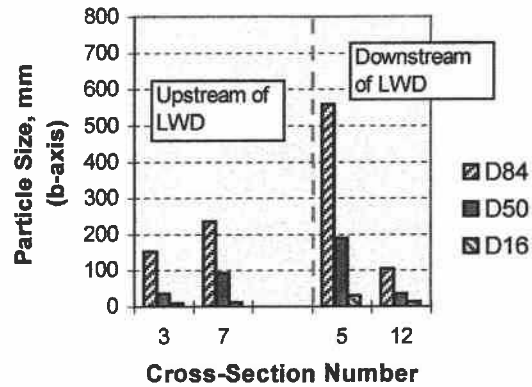
The finding that the bed material was slightly finer in the clearcut reach than in the old-growth reach in 1995 (Figure 4.10) was contrary to the expectation that there would be more relatively fine bed material (i.e., gravel and small cobbles) in the old-growth reach due to the increased hydraulic roughness and sediment storage capacity associated with LWD. It is possible that the streambed in the clearcut reach was anomalously fine in 1995 due to release of a wedge of fine sediment upstream up the road crossing (Figure 3.2) when the culvert formerly at that location was removed and replaced by the current bridge in September 1994 (Gregory, personal communication). If so, the coarsening observed in the clearcut reach in association with the February 1996 flood could be partially a result of channel adjustment to this prior disturbance. Unfortunately, particle size data were not collected in association with the cross section surveys prior to 1995, so it is impossible to tell whether or to what degree bed texture in the clearcut reach was affected by release of stored fine sediment due to removal of the culvert. The cross section data for the clearcut reach, however (Appendix B), do not show any evidence of significant, widespread aggradation between 1990 and 1995 that would indicate a substantial influx of gravel to the reach.

The largest patches of relatively fine, readily transportable bed material (gravel and small cobbles) were typically observed just upstream of log steps and LWD jams (Figures 4.2, 4.4). This observation is supported by the particle size data. Cross sections located immediately upstream of channel-spanning LWD structures tended to have significantly finer bed material, particularly at the coarse end of the size distribution, than the reach as a whole. Cross sections located immediately downstream of LWD structures tended to have bed material somewhat coarser than the reach average (Figure 4.11). The fining effect of LWD structures on upstream particle size was particularly pronounced. In the 2 post-flood years (1996 and 1997), the three cross sections located upstream of LWD structures (XS 3, 7 and 10) had the smallest D_{84} values of all 12 old-growth cross sections (Appendix A).

(a) 1995

Summary of Particle Size Statistics--1995

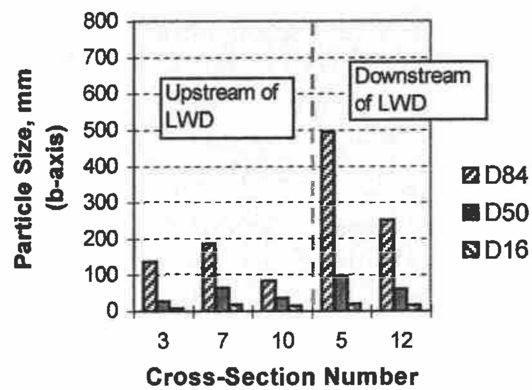
Section No.	D_{84}	D_{50}	D_{16}
Upstream of LWD			
3	152	35	8
7	234	92	11
Combined	**205**	**64**	**9**
Downstream of LWD			
5	558	189	30
12	105	36	13
Combined	**322**	**64**	**16**
Entire Reach	***302***	***77***	***17***



(b) 1996

Summary of Particle Size Statistics--1996

Section No.	D_{84}	D_{50}	D_{16}
Upstream of LWD			
3	136	27	7
7	184	64	17
10	84	35	15
Combined	**136**	**40**	**11**
Downstream of LWD			
5	494	95	19
12	251	61	16
Combined	**408**	**67**	**16**
Entire Reach	***302***	***66***	***16***



(c) 1997

Summary of Particle Size Statistics: 1997

Section No.	D_{84}	D_{50}	D_{16}
Upstream of LWD			
3	222	54	11
7	250	80	14
10	190	72	21
Combined	**222**	**65**	**14**
Downstream of LWD			
5	803	211	62
12	400	81	10
Combined	**625**	**147**	**22**
Entire Reach	***370***	***98***	***21***

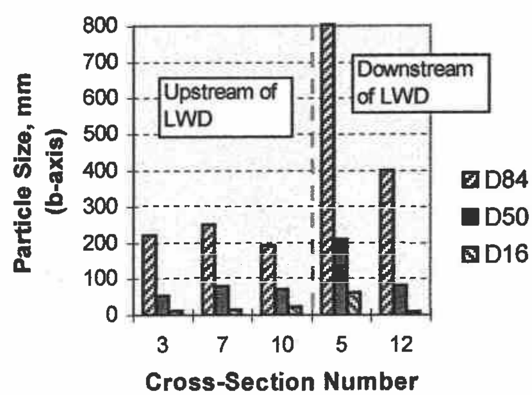


Figure 4.11. Bed surface particle size at cross sections located within one channel-width upstream and downstream of LWD structures, MAC site: (a) 1995; (b) 1996; (c) 1997. Values for "Entire Reach" are for pooled samples and differ from those shown in Table 4.3, which are averages of D_i values for individual cross sections.

5 Discussion

5.1 Geomorphic Functions of Static and Moving LWD

LWD influences channel morphology and channel change principally by promoting or retarding channel bed scour or bank erosion, promoting deposition and anchoring sediment, or some combination of these effects. Key LWD pieces can influence channel and flow geometry individually or in accumulations. Borrowing from Nakamura and Swanson (1993), a key piece is defined here as a LWD piece that anchors a significant sediment accumulation or is a structural member of a LWD jam and which is large enough to span the main channel at constrictions. A potential key piece is a LWD piece which is large enough to function as a key piece but which does not currently anchor a sediment accumulation or form part of a LWD jam. The most geomorphically effective LWD (in terms of influencing channel form and sediment transport) are key pieces which form channel-spanning log steps or LWD jams, which can significantly modify both channel pattern and longitudinal profile. Marginal LWD pieces and accumulations can also influence channel geometry locally and anchor limited marginal sediment accumulations.

Most previous work on LWD interaction with channel morphology has focussed primarily on the role of stationary LWD accumulations within the channel. Such *static LWD*—individual pieces or accumulations that remain in place but can interact dynamically with flow and sediment—can influence both present channel morphology and temporal patterns of channel adjustment (Nakamura and Swanson, 1993). However, it is also important to consider the role of LWD as a dynamic structural element of the channel. *Dynamic LWD* can be defined as individual pieces that move or that enter the channel during a particular event or specified time period. It also includes LWD structures that are formed, substantially expanded, or partially or completely dismantled during the specified event or time period. LWD that moves during a particular event can interact with sediment and affect channel morphology at both the old and new locations.

Major static and dynamic effects of individual key pieces and LWD jams in intermediate size streams such as Mack Creek, which are capable of occasionally redistributing at least some fraction of their key LWD, are summarized in Table 5.1. Both channel-spanning individual key pieces that form log steps (requiring a relatively horizontal orientation) and LWD jams can accumulate an upstream sediment wedge, divert flow laterally to cause bank erosion, widen the channel through bank erosion or sideslope failure and channel filling, and cause upstream fining and downstream coarsening of the bed surface. But LWD jams appear to have a greater tendency to cause channel widening (Table 4.1), and also are probably more dynamic sediment storage sites than log steps. Once a flat-lying channel-spanning key piece begins to trap sediment, it tends to quickly become buried on the upstream side, raising the bed of the stream and establishing a new local base level (Figure 4.2). Log steps are particularly stable sediment storage sites similar in function to check dams. LWD jams, on the other hand, tend to be both higher and "leakier" than log steps. The crest of LWD jams typically protrudes well above the bed (Figures 4.3, 4.4), unlike log steps in which the step crest typically is part of the bed, at least partially submerged even at low flow. The arrangement of the key pieces, or of smaller LWD and organic debris which regulate the permeability of the LWD jam to water and sediment, may shift from time to time, causing release of stored sediment or additional sediment impoundment. Time-lapse photography at two locations upstream of LWD jams (features 2 and 4 in Figure 3.2) and anecdotal observations of researchers who have worked at Mack Creek over a 20-year period confirm that the channel immediately upstream of LWD jams is a particularly dynamic environment (Gregory, personal communication).

5.2 Influence of LWD on Channel Characteristics

Channel-spanning LWD structures—log steps and LWD jams—create pronounced steps in the longitudinal profile (Figure 4.1). These structures create upstream low-gradient or backwater hydraulic environments (depending on flow) which constitute particularly stable sediment storage sites where bed material tends to

Table 5.1. Effects of static and dynamic LWD on channel morphology and channel adjustment in high-gradient streams of intermediate size.

Type of Structure	Static Effects	Dynamic Effects
Channel-spanning key piece	▪ Accumulate upstream sediment wedge, causing aggradation and moderate to long-term sediment storage. ▪ Divert flow laterally into bank, promoting bank erosion and scour ▪ If suspended, anchor marginal sediment and/or OD accumulation on lower end, and possibly cause enhanced scour and pool formation beneath or downstream of suspended portion ▪ Promote upstream fining and possibly downstream coarsening of bed material.	Same as static effects, plus: ▪ Channel degradation associated with removal of step-forming log. ▪ Channel-margin scour associated with removal of a log anchoring a marginal sediment/OD accumulation
LWD jam	▪ Accumulate large sediment wedge, causing substantial local aggradation. ▪ Periodically release sediment, causing upstream scour and deep pool formation. ▪ Widen channel through bank erosion and sediment deposition. ▪ Periodically shift main thalweg from side to side of upstream sediment wedge, causing local scour and fill within the channel. ▪ Promote upstream fining and possibly downstream coarsening of bed material.	Same as static effects, plus: ▪ Major degradation with upstream and downstream scour when jam blows out.
Marginal key piece or LWD accumulation	▪ Create/stabilize marginal bars and OD accumulations, typically upstream of piece. ▪ Protect/stabilize existing mid-channel bar (downstream of piece)	Same as static effects, plus: ▪ Destabilize marginal or mid-channel bar when floated out; promote local scour. ▪ Block side-channel entrance, promoting sediment deposition in and/or abandonment of side channel. ▪ Reactivate and scour side channel when LWD accumulation at channel entrance is washed out.

be finer than elsewhere in the channel (Thompson, 1995). This type of hydraulic environment can be of particular importance to aquatic organisms (Statzner et al., 1988).

Although log steps (Figure 4.2) are smaller structures than LWD jams (Figure 4.3), both have a similar magnitude of effect on the longitudinal profile of Mack Creek at the old-growth site (Figure 4.5[a]). On a longitudinal bed elevation residual plot, peaks associated with log steps have similar height but somewhat shorter, steeper rising limbs compared with peaks associated with LWD jams. Thus, the log steps have lower-gradient channel upstream than do the LWD jams, but this effect does not extend as far upstream as it does for jams. It is worth noting that while LWD jams do show up as peaks in a longitudinal plot of in-channel LWD volume (top plot in Figure 4.7[a]), log steps do not, despite their obvious geomorphic significance. Thus, longitudinal surveys of LWD loading (number of pieces, volume, or mass of LWD per unit channel length or area) alone are not sufficient to predict or characterize the effects of LWD on channel morphology, at least not on a local scale.

Particle size sample results from this study are consistent with previous studies that have shown that LWD provides depositional sites for finer bed material (e.g., Beschta, 1979; Bilby, 1981; Thompson, 1995). In particular, bed material particle size sampled within one channel-width upstream of channel-spanning LWD structures in the old-growth reach at Mack Creek was consistently finer than the reach-average particle size across the entire particle size distribution (D_{84}, D_{50}, D_{16}) for all three years (1995-97) in which particle size was sampled (Figure 4.11). At the reach scale, the influence of LWD on particle size is less clear. As reported in Section 4.2.3, the bed surface was slightly (but not significantly) finer in the clearcut reach than in the old-growth reach in 1995, but was significantly coarser in the clearcut reach than in the old-growth following the February 1996 flood (Figure 4.10, Table 4.3). The influence of structural LWD on particle size in Mack Creek thus appears to be most significant at a local scale (e.g., the scale of individual cross sections). At the reach scale, the effect of LWD manifests as a greater within-reach variability in particle size, as reflected by field observations (e.g., Figures 4.2 and 4.3) and by the consistently greater coefficient of variation of the D_{84}, D_{50}, and D_{16} statistics for the old-growth cross sections vs. the clearcut cross sections for all three years during which particle size data were collected (Appendix A).

5.3 Influence of LWD on Channel Response to the Flood of February 1996

Nakamura and Swanson (1993) found that the largest and most frequent cross section changes observed in 5^{th}-order Lookout Creek over a 10-year period (1978-88) were associated with newly input and static key LWD pieces. The largest changes occurred in the winter of 1981-82, when four old-growth trees fell into a 75-m section of the channel, and during the 1986 water year, when a moderately large (5.5-year recurrence interval) flood occurred. Thus, it might be expected that the largest cross section changes in Mack Creek in response to the February 1996 flood would be associated with key LWD—in particular, log steps and LWD jams. This would be consistent with the hypothesis that key LWD increases the local variability in channel response to floods while reducing channel change at the reach scale.

The response of the Mack Creek channel to the February 1996 flood was consistent with these expectations. Although there was no apparent association between the volume of LWD within the channel and magnitude of cross section change, log steps and LWD jams were clearly associated with substantial upstream deposition in response to the 1996 flood, which produced the largest observed cross section changes in the old-growth reach (Figure 4.7[a]). At the reach scale, this resulted in a more patchy channel response within the old-growth reach than was observed within the clearcut reach (Figure 4.7). Thus, the specific arrangement of key LWD within the channel was much more important than variations in the quantity of LWD in determining channel response to the 1996 flood.

The geomorphic function of a key piece may change dramatically even when the piece does not move. This fact is illustrated by the log step just downstream of XS 3 (Figure 3.2). The log forming this step is a bigleaf maple toppled by bank erosion that was classified in the LWD database as having 60% of its volume in zone 3 (in the channel above bankfull stage), but as of summer 1996 the log formed part of streambed, with water spilling over it even at low flow. Without moving, this log changed over time from being suspended above the channel to forming part of the bed by accumulating a substantial upstream sediment wedge. Thus, because new data on the position and other characteristics of a piece are collected only when the piece is inferred to have moved since the previous survey, major changes in the functional role and importance of key or potential key pieces can go undetected by the LWD inventory surveys.

5.4 Influence of LWD on Sediment Storage and Transport

Channel-spanning LWD clearly creates major sediment storage sites within the old-growth reach at Mack Creek. By creating large steps in the longitudinal profile of the channel (Figure 4.1), channel-spanning log steps and LWD jams trap large sediment wedges. Since such LWD accumulations also tend to widen the channel, the volume of sediment that they can store in the upstream wedge is considerable. Thompson (1995) argues that pools upstream of LWD represent particularly stable sediment storage sites; because they represent low-gradient, backwater environments even at high flows, sediment stored in pools upstream of LWD will likely have a longer residence time than sediment stored in scour or plunge pools located downstream of flow obstructions or sediment stored in bars or riffles. No channel-spanning LWD or analogous sediment storage sites are present in the clearcut reach. Thus, it is likely that both the volume and mean residence time of sediment stored in-channel in the clearcut reach are less than in the old-growth reach.

Bedload transport or sediment volume stored in the channel were not measured or estimated in this study. However, the cross section surveys and associated particle size data provide direct evidence of changes in sediment storage and, hence, indirect evidence of sediment transport in the old-growth and clearcut reaches during the winter of 1995-96. These data suggest significant differences in the movement of sediment within the two reaches. In general, the clearcut reach was dominated by channel scour and coarsening of the bed material (Table 4.2), suggesting a net loss of sediment from the reach due to selective transport of finer bed material. In contrast, substantial aggradation (i.e., an increase in sediment storage) occurred at all three locations in the old-growth reach where cross sections are located immediately upstream of channel-spanning LWD (XS 3, 7, and 10; Table 4.2), accompanied in two of the three locations by a distinct decrease in bed surface particle size. At the reach scale, no significant change in particle size was observed in the old-growth reach between 1995 and 1996 (Figure 4.10, Table 4.3).

The importance of channel-spanning LWD in creating stable sediment storage sites, particularly for relatively fine bedload, is underscored by the fact that all three cross sections in the old-growth reach where aggradation occurred in response to the February 1996 flood were located within one channel-width upstream of a log step or LWD jam. Further, even though this was the largest flood in a 20-year record, both of the pre-existing structures apparently increased their sediment accumulations. In the clearcut reach, where no channel-spanning or geomorphically significant LWD was present, significant but minor net channel fill also occurred at three cross sections (XS 103, 105, and 110; Table 4.2). However, aggradation at these locations was accompanied by coarsening of bed material at all three locations, not fining as in the aggraded old-growth cross sections.

These results and the much more pronounced 1995-96 particle size response (coarsening) in the clearcut reach as opposed to the old-growth reach (Figure 4.10) support the claim that LWD decreases the sediment transport efficiency of a channel (e.g., Heede, 1977; Marston, 1982; Adenlof and Wohl, 1994; Montgomery et al., 1996). Channel-spanning LWD in the old-growth reach at Mack Creek trapped a significant quantity of sediment during the February 1996 flood, and may have been instrumental in preventing more extensive channel scour or a measurable reach-scale textural response to the flood. In the clearcut reach, where channel-spanning LWD is absent, much more extensive channel scour and a measurable reach-scale coarsening of the bed material occurred. We can infer from this that bedload sediment was more efficiently transported through (and out of) the clearcut reach than the old-growth reach. As a result, the clearcut reach was somewhat sediment-starved during the February 1996 flood, to which condition it responded by general down-cutting and coarsening of its channel.

5.5 Limitations of Study Design and Recommendations for Future Modifications

Although the two long-term data sets used in this study have a greater length of record and, in the case of the LWD data, are far more detailed than those that have been previously reported in published studies, they nonetheless suffer a number of limitations. First and perhaps foremost, cross sections may not be the most appropriate tool for monitoring channel change in steep mountain streams. Since the chief effect of LWD on channel morphology in such streams is the creation or modification of a stepped channel profile (Keller and Swanson, 1979; Nakamura and Swanson, 1993; Thompson, 1995), in which channel structure is predominantly expressed through variations in channel slope and bed texture (Grant et al., 1990; Montgomery and Buffington, 1997), cross section surveys may not adequately characterize the spatial structure or the temporal variation of spatial structure in these streams. Repeated longitudinal profile surveys might be more appropriate for this purpose, but are inherently less repeatable (hence less readily comparable between years) than cross section surveys.

A limitation more specific to the Mack Creek site is the relatively small number and irregular spacing of reference cross sections, particularly in the old-growth reach. Additional cross sections upstream of section 12 (Figure 3.2) and more even cross section spacing would have been helpful. Only two cross sections in the data set (only one before 1996) were located within a channel width or so (i.e., clearly within the sediment accumulation zone) of log steps and only one was located immediately upstream of a LWD jam, while two cross sections were located immediately downstream of LWD jams and none were located downstream of log steps (Figure 3.2). This limited "sample size" of cross sections having an unambiguous spatial relationship to significant LWD structures severely constrains the usefulness of the cross section data set for evaluating the effects of LWD on channel form and process.

Several difficulties arise from trying to use the cross section and LWD data sets together due to their different spatial structure. The LWD data are essentially a discretized longitudinal transect derived from data that are inherently two-dimensional (i.e., the map position and characteristics of LWD within and adjacent to the channel). The cross section data set, on the other hand, are an inherently one-dimensional data set (i.e., bed elevation as a function of cross-channel distance) that is oriented orthogonal to the LWD transect. Further, the spatial grain of the LWD data (which at 10 m is smaller than many individual LWD pieces, which can span multiple segments on the LWD baseline), is coarse relative to that of the cross section data (0.5 m). For example, sub-grain (hence, undetectable) LWD movement, such as pivoting of a single large log, might induce significant changes in a cross section profile. Also, since the spatial grain of the LWD data is not much smaller than the spacing between cross sections (i.e., the grain of the cross section data for between-section comparisons), and since a cross section can fall anywhere between the upstream and downstream boundaries of a LWD baseline segment, the spatial relationship between individual cross sections and LWD data points is inexact and variable. These problems become less significant at greater spatial scales. Thus, there is little problem relating LWD and cross section data at the reach scale (i.e., old-growth vs. clearcut reach), but relating them at the scale of individual cross sections to make between-section comparisons becomes more problematic, and the LWD data are of little value for explaining within-section changes.

These considerations suggest some modifications to the current monitoring program that could improve the usefulness of the data collected. Cross section locations should be selected to sample a representative selection of channel environments based on channel unit type (e.g., pool, riffle, etc.) and LWD influence. For example, cross sections could be established in the zones of up- and downstream influence of existing log steps and LWD jams—say, within a distance of one-half of the active channel width up- or downstream of these structures. More regular, frequent spacing of cross sections within the old-growth reach, at a spacing of approximately one active channel width as in the clearcut site, would ensure a reasonably representative sampling of different channel environments within the reach even when LWD is rearranged and channel units are changed by future floods.

Because channel configuration and LWD influence can change over time, changes in these characteristics should be noted when cross sections are resurveyed.

The channel unit type and local channel slope—measured over the length of the channel unit containing the cross section or over a fixed distance such as 5 m (roughly one-half the average active channel width) up- and downstream of the cross section line—should be measured and recorded each time the cross sections are surveyed. During the annual LWD inventory, changes in the function of a piece of LWD or its position relative to the channel should be noted even when there is little or no movement of the piece. For example, if a log that was perpendicular to the channel is pivoted to a position against the bank, or a log which was suspended above the channel captures a wedge of bedload to become a log step, these are important changes that should be recorded.

6 Conclusions

Log steps and LWD jams create distinctive, 1.5- to 3-m high steps in the channel profile of Mack Creek, accounting for about 30% of the total channel relief in the old-growth reach and zero percent in the clearcut reach. Log steps and LWD jams increase the variability in local channel width, slope, and bed surface particle size, providing diverse physical habitat that may be important to aquatic organisms. Bed material size and channel slope are both reduced upstream of channel-spanning LWD structures. In Mack Creek, which has an average longitudinal valley floor slope of 9.7%, 23% of the channel length within the old-growth reach has a local slope (measured at a scale approximating the average channel width) of 5% or less, compared with just 7.5% of the channel in the clearcut reach.

LWD jams are correlated spatially with locally increased channel width and frequency of large, immobile boulders exposed in the bed. Many of these large boulders are probably immobile even during extreme floods, and may represent relict deposits from non-fluvial processes (e.g., glaciers, debris flows, or landslides). These immobile boulder lag deposits may underlie much of the streambed where bedrock is not exposed, but are exposed downstream of LWD jams and buried upstream.

Channel-spanning LWD structures provide an important mechanism for energy dissipation (Marston, 1982). Acting as large roughness elements in the channel that create diverse hydraulic environments (Gippel, 1995; Lisle, 1995), log steps and especially LWD jams increase reach-scale channel stability while increasing local spatial variability in channel response to particular flood events. The response of Mack Creek to a large flood in February 1996 with an estimated recurrence interval of 23.5 years is consistent with this hypothesis. The clearcut reach exhibited predominantly channel scour and pervasive coarsening of the channel bed. In the old-growth reach, in contrast, the magnitude and extent of channel scour were less, scour was interspersed with substantial aggradation upstream of LWD structures, and bed surface particle size changes were mixed. The old-growth reach also exhibited a finer spatial scale of variation (i.e., more frequent transitions between scour and fill or coarsening and fining; see Table 4.2) than did the clearcut reach.

Log steps and LWD jams are a major control on sediment storage and transport in Mack Creek. During the February 1996 flood there was substantial movement of bed material in both the old-growth and clearcut reaches, as indicated by the large observed changes at cross section locations. However, the average net change (total fill minus total scour) for the old-growth cross sections was only -0.05 m^3/m, while for the clearcut cross sections it was -1.50 m^3/m (Figure 4.8), suggesting that a significant quantity of sediment was lost from storage within the clearcut reach but that no net change in storage occurred within the old-growth reach.

Cross sections and longitudinal surveys of LWD abundance and size distribution are commonly used tools for assessing interactions between LWD and channel morphology and process, but they are not necessarily the best tools for this job, depending upon the channel gradient and the spatial scale of interest. In high-gradient, narrow mountain streams, channel structure and variability is primarily expressed along a longitudinal vertical plane through the development of a stepped longitudinal profile, which limits the usefulness of channel cross sections. While the influence of LWD on channel structure and channel change at the reach scale depends largely upon the quantity and size distribution (relative to channel width) of LWD in the channel, at finer scales it depends critically upon the location, arrangement and structure of LWD within the channel. Thus, detailed information about the spatial arrangement and geomorphic function or context of individual LWD pieces and accumulations is critical to understanding LWD-channel interaction at sub-reach scales.

Part II: Frequency, Magnitude, and Spatial Patterns of Channel Response to Peak Flows in a Mountain Watershed

7 Introduction

Mountain streams comprise the headwaters of most major river systems. They generate floods, provide sediment and wood to downstream rivers, and serve as refuges or critical habitat for many species, both aquatic and terrestrial. In the Pacific Northwest, they frequently occupy watersheds that provide timber products and/or water supply for downstream users. Understanding mountain stream channel response to natural or anthropogenic stresses (e.g., floods or changes in streamflow or sediment load) is relevant to all these functions.

The morphology and dynamics of mountain streams differ markedly from those of lowland streams, but until recently have been much less well studied (Grant and Swanson, 1995). Whereas large, low-gradient streams have channels and associated valley floor landforms shaped almost entirely by fluvial processes and are able to rework their channels at least every one to two years (Wolman and Miller, 1960), high-gradient mountain streams are strongly influenced by processes and landforms external to the channel (Grant et al., 1990; Grant and Swanson, 1995). Extreme storms trigger mass movements such as landslides and debris flows, which leave lasting impacts on valley landforms in mountainous environments (Hack and Goodlett, 1960; Wolman and Gerson, 1978; Nolan and Marron, 1985; Swanson et al., 1985). However, mountain stream channels are also subject to gradual, prolonged external influences, notably impingement upon the active channel by alluvial fans and large, slow-moving earthflows (Vest, 1988). These can constrain the channel laterally, influence up- and downstream channel gradient, and deliver coarse sediment and boulders that the stream can move only infrequently during unusually large flows (Wolman and Miller, 1960; Grant, 1986; Grant et al., 1990). Bedrock also plays an important role in controlling channel and valley floor morphology in mountain streams (Lisle, 1986; O'Connor et al., 1986; Grant et al., 1990). Hence, changes in mountain stream channel and valley floor morphology are both episodic and continuous, and depend strongly upon the character of the valley floor and the surrounding landscape.

Stream channels and adjacent valley floor surfaces in mountain watersheds are strongly affected by hillslope processes that deliver particulate matter—i.e., sediment, wood, and organic debris over a wide range of sizes—to the channel. These include slow, chronic or continuous processes such as particle-by-particle transport by surface erosion; slow, continuous downslope bulk movement of soil and weathered bedrock by creep; movement of soil, rock and organic material associated with uprooting and downhill sliding of trees (root throw); and slow, deep-seated downslope displacement of large masses of soil and weathered bedrock by earthflows (Swanson et al., 1982a). Detachment and rapid downslope transport of soil, trees and other organic debris—alternately termed debris avalanches or debris slides—can initiate debris flows in small, steep, low-order channels or deliver large pulses of sediment and organic matter directly to larger channels (Swanson et al., 1987). Debris flows (also called debris torrents) are rapid channelized mass movements of water, sediment, and organic matter which can scour low-order channels to bedrock and deliver large volumes of material (up to 10,000 m^3 or greater) to larger streams or to depositional sites within 2nd - to 3rd-order channels or on alluvial fans or valley floors (Swanston and Swanson, 1976; Swanson et al., 1982a; Swanson et al., 1987). Debris slides and debris flows are episodic processes that occur only in association with large storms, delivering large pulses of sediment and organic material to stream channels at many locations within single watershed (Swanson and Dyrness, 1975; Grant, 1986; Nakamura et al., in press; Snyder, in preparation).

These processes do not operate uniformly within a watershed. Their spatial distribution upon the landscape is controlled by topography, geology, and channel network structure, and has important consequences for the morphology and dynamics of mountain stream channels (Grant et al., 1990; Grant and Swanson, 1995; Montgomery and Buffington, 1997; Montgomery, 1999), and for stream and riparian ecosystems (Swanson et al., 1998). Within mountain watersheds, strong contrasts in channel morphology and the dynamics of channel disturbance occur between steep, confined low-order tributaries and larger mainstem (4th to 5th-order) streams. Low-order tributaries are strongly coupled to adjacent hillslopes, where tree fall and hillslope mass movements such as landslides and earthflows can deliver material to the stream that it is incapable of moving even at high flows (Scott and Gravlee, 1968; Grant, 1986; O'Connor et al., 1986; Grant et al. 1990). Larger (4^{th}- to 5^{th}-order) mainstem streams, like lowland streams, typically are bordered at least in places by alluvial valley floor landforms such as floodplains and terraces which insulate them to some degree from the valley walls and associated mass wasting processes (Grant and Swanson, 1995; Montgomery and Buffington, 1997).

Montgomery and Buffington (1997) have suggested that a gradient of increasing dominance of fluvial processes in the downstream direction occurs within mountain watersheds as one moves from steep colluvial channels where channel formation is controlled principally by debris flows (Benda, 1990; Seidl and Dietrich, 1992) to lower gradient alluvial channels in which fluvial processes are dominant. Building upon the ideas of Gilbert (1877, 1914, 1917), Lane (1955) and Schumm (1969), they propose that channel morphology reflects an adjustment to the ratio, q_r, of transport capacity (Q_c) to sediment supply (Q_s). Specifically, they postulate that mountain stream channels adjust their beds to achieve an equilibrium in response to a systematic downstream decrease in q_r. Their conceptual framework implies a general downstream progression from very high-gradient "source" reach types dominated by hillslope and non-fluvial processes ($q_r << 1$) to moderate-to-high gradient "transport" reach types ($q_r >> 1$) and lower gradient "response" reach types ($q_r \leq 1$) dominated by fluvial processes.

While Montgomery and Buffington posit a downstream trend of increasing fluvial control and decreasing influence of non-fluvial processes on channel morphology and dynamics at the watershed scale, Grant and Swanson (1995) attributed patchy patterns of riparian and channel disturbance to reach scale variations in the degree to which mainstem channels in mountain watersheds are constrained by hillslopes; bedrock outcrops; and valley floor landforms such as terraces, earthflows, and tributary alluvial fans. Where streams are narrow and constrained by adjacent landforms, channel gradients are higher than average and flows during floods are deep, leading to high shear stresses that promote erosion of the channel bed and banks and uprooting of riparian vegetation. Where the valley floor is wide and the stream is laterally unconstrained, shear stresses are lower and deposition and lateral changes in channel position become the dominant form of channel disturbance (Grant and Swanson, 1995). Grant and Swanson (1995) concluded that the ratio of channel to valley flood width was the primary factor controlling where large floods scour and deposit sediment in mountain streams.

Because mountain streams often flow through forested landscapes and are both narrower and shallower than lowland rivers, large woody debris (LWD) plays a key role with respect to channel morphology and disturbance in many mountain streams. In small (1^{st} to 3^{rd}-order) channels, much of the available LWD is longer than the channel width and seldom if ever moves until it decays sufficiently to break into smaller pieces or is transported by a debris flow (Nakamura and Swanson, 1993). Wood typically comprises a major structural element in low-order stream channels, strongly influencing channel morphology (e.g., Keller and Swanson, 1979; Marston, 1982; Bilby, 1984; Nakamura and Swanson, 1993), and in some cases even controlling the distribution of alluvial vs. bedrock channel reaches (Montgomery et al., 1996). Smaller pieces that are close to or less than channel width in length interact the most strongly with sediment and have the greatest impact on channel structure and dynamics. In larger mainstem (4^{th} to 5^{th}-order) channels, LWD is relatively more mobile due to greater channel width and flow depth (Swanson and Lienkaemper, 1978; Lienkaemper and Swanson, 1987). LWD is less important as a structural element of the stream channel than in low-order tributaries, but perhaps more important as an agent of riparian vegetation disturbance. (Swanson et al., 1998; Johnson et al., in press). Large whole logs, or "key pieces" (Nakamura and Swanson, 1993) are most important in terms of their effect on channel form and the dynamics of channel and riparian disturbance.

Recent research into drainage basin and channel morphology and the processes which shape and disturb stream channels and valley floors in mountain watersheds have included many excellent theoretical and modeling studies (e.g., Wiberg and Smith; 1987; Furbish, 1993; Miller, 1995; Iverson, 1997), and laboratory flume experiments (e.g., Dietrich et al., 1989; Grant and Mizuyama, 1991; Braudrick et al., 1997). Field-based investigations have attempted to quantify long-term rates of geomorphic processes (Dietrich and Dunne, 1978; Reneau and Dietrich, 1990); study rates, mechanisms, and interactions of processes from short-term observations (e.g., Dietrich and Smith, 1983; Dietrich et al., 1984; Wiberg and Smith, 1991; Whiting, 1997); or relate channel or valley floor characteristics to suites of gemorphic processes inferred to be responsible for their formation or modification using synoptic observations or measurements (e.g., Grant et al., 1990; Lisle and Madej, 1992; Montgomery and Dietrich, 1992; Grant and Swanson, 1995; Montgomery and Buffington, 1997).

Fewer published field studies have employed plot or transect-based repeated observations at relatively frequent intervals (i.e., seasonal to annual) over extended time periods (i.e., decades) to look at the dynamics of channel or landform change at annual to decadal time scales. This is not surprising, given that generating such long-term data sets requires considerable institutional investment and commitment over an extended period. One place where such studies have been done is Redwood Creek, California. Since the mid 1950s, annual cross section surveys at 58 locations distributed along the entire length of the creek and periodic longitudinal profile surveys have been used to monitor channel response to massively increased sediment yields resulting from timber harvest and associated road building effects in combination with several major floods in the mid 1950s through the mid 1970s (e.g., Nolan and Marron, 1995; Madej and Ozaki, 1996; Madej, in press).

This study draws on up to 50 years of streamflow data and 20 years of quasi-annual cross section monitoring data to explore the dynamics of channel response to peak flows on an approximately annual time scale at five 2nd to 5th-order stream reaches arrayed within a 5th-order, 64 km^2 watershed in the Western Cascades of Oregon (Figure 3.1). This unique data set provides an opportunity to evaluate how the relationship between channel response and peak flow magnitude or frequency varies between streams of different order within a single watershed in which both the natural history and land management activities have been well documented. The overall goal of this research was to characterize the frequency, magnitude and spatial patterns of channel response to peak flows in the Lookout Creek watershed and to test hypotheses proposed in the fluvial geomorphology literature about controls on the response of mountain stream channels to peak flow events. Specific objectives included the following:

1. Develop methods for characterizing channel response to floods at the channel unit to reach scale using historical cross section monitoring data.
2. Establish an empirical relationship between peak flow magnitude or recurrence interval and observed measures of cross section change.
3. Use the results of (1) and (2) to infer the frequency of peak flow events required to (a) initiate significant bedload transport or (b) substantially rework the channel bed at the cross section sites, and to assess whether between-site differences are consistent with expectations based on hypotheses proposed in recent geomorphologic literature.
4. Explore watershed scale spatial patterns in channel response to peak flows, with particular attention to differences between 2nd to3rd-order tributaries and 4th to 5th-order mainstem streams.
5. Assess whether the relationship between flood magnitude and observed cross section response (objective 2 above) is affected by a major channel-restructuring flood such as the flood of February 1996—i.e., can a major flood alter the susceptibility of the channel to disturbance by subsequent floods?

8 Conceptual Approach

8.1 Spatial Variation in Geomorphic Processes with a Mountain Watershed

The Process Domains Concept (PDC; Montgomery, 1999) provides a useful framework for thinking about how dominant disturbance processes vary spatially within a mountain watershed and how this spatial variability governs both temporal patterns of channel and riparian disturbance and spatial patterns of habitat characteristics within the channel network. The basic premise of the PDC is that spatial variability in geomorphic processes controlled by topography, geology, and climate governs spatial and temporal patterns of physical and biotic disturbances that in turn influence ecosystem structure and dynamics. Figure 8.1 shows how physical disturbance processes and associated habitat characteristics are hypothesized by the PDC, as interpreted by the author, to vary spatially within the channel network in a typical Pacific Northwest mountain watershed, where debris slides and debris flows are important mass wasting processes.

Flood-related disturbance processes vary both with channel size or position within the drainage basin (Figure 8.1), and with flood magnitude (Figure 8.2). Disturbance of benthic and hyporheic habitat beneath the streambed begins when discharge increases sufficiently to initiate significant bedload transport within the channel thalweg. Substantial disturbance of riparian vegetation does not begin until flood stage increases sufficiently to begin to mobilize LWD (Figure 8.2), which then becomes a "tool" which greatly increases the effectiveness of floodwaters in battering and toppling riparian vegetation (Swanson et al., 1998; Johnson et al., in press). Truly major floods trigger widespread hillslope mass movements such as shallow debris slides and streamside slides, which can enter channels and cause "disturbance cascades" (Nakamura et al., in press) which propagate down the channel network. For example, a debris slide entering a low-order channel may become debris flow, which moves down the channel network and may enter a mainstem channel, where it may trigger a wood-rich flood surge. These disturbance cascades produce a gradient of

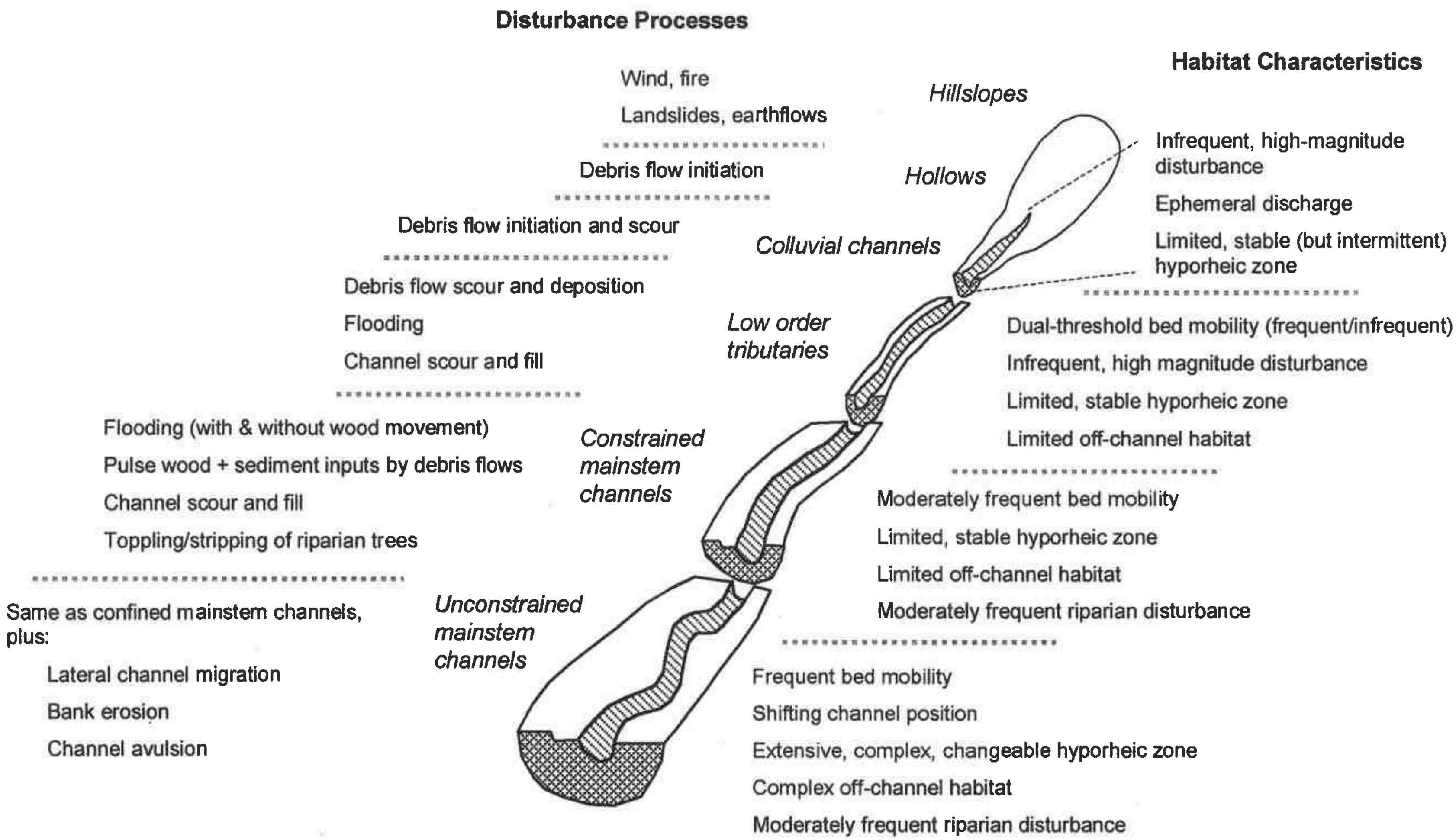


Figure 8.1. Schematic illustration of stream channel network showing characteristic disturbance processes and associated habitat characteristics for different portions of the channel network. (Modified from Montgomery [1999].)

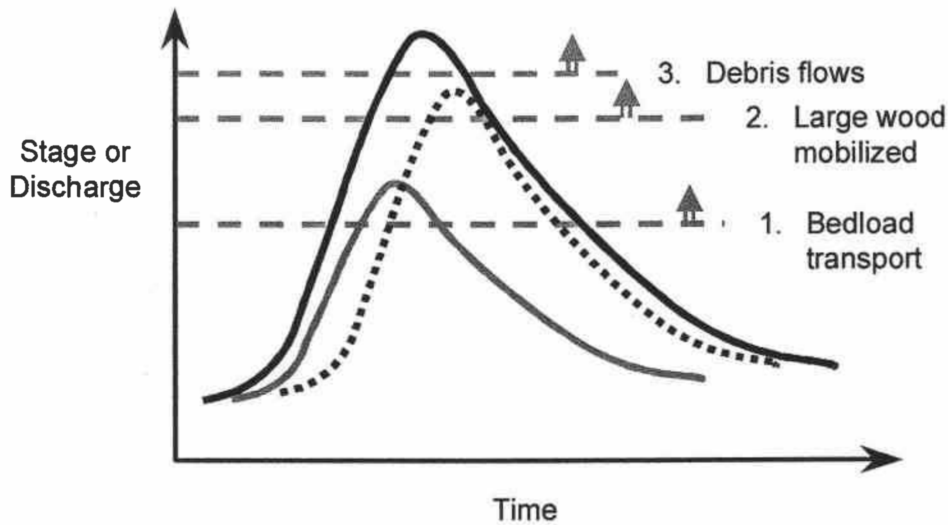


Figure 8.2. Disturbance processes as a function of flood magnitude. At moderately high discharge (1), bedload transport begins. During large floods (2), large wood is mobilized and can become a "tool" for battering riparian vegetation and banks. Major floods can trigger debris flows (3), causing direct scour and deposition in low order tributaries and providing large pulse inputs of wood and sediment to mainstem channels, greatly augmenting the potential geomorphic effectiveness of the flood.

stream and riparian disturbance of decreasing overall severity and increasing variability in severity in the downstream direction (Nakamura et al., in press).

Debris flows are a key process governing channel disturbance during major floods in both low-order tributaries and mainstem channels. Snyder (in preparation) found that debris flow related disturbances affected approximately 15% of the total channel network in the Lookout Creek watershed. In low-order tributaries, debris flows rework the channel through direct scour and deposition, primarily scour in 1st and 2nd-order channels and deposition in 3rd or higher order channels (Snyder, in preparation). Debris flows entering mainstem (4th-order or higher) channels can contribute large (1000s of m^3) volumes of wood and sediment, which can greatly magnify the geomorphic effectiveness of the flood in the receiving channel (Swanson et al., 1998; Wondzell and Swanson, 1999; Johnson et al., in press; Nakamura et al., in press).

The downstream variation in disturbance processes in Figure 8.1 reflects the gradual downstream decoupling of stream channels from adjacent hillslopes. At the tips of the channel network are bedrock hollows, which are small, unchanneled valley heads where thick sediment colluvial deposits gradually accumulate by soil creep, raveling and biogenic transport (e.g., roothrow and burrowing). Increasing soil thickness in combination with convergent patterns of surface and subsurface runoff in hollows leads to periodic evacuation of colluvial sediment by catastrophic debris slides with a natural recurrence interval on the order of thousands of years (Reneau and Dietrich, 1990, 1991). Immediately downslope of hollows are steep, ephemeral colluvial channels where the fluvial sediment transport is weak (Montgomery and Buffington, 1997). Here, scour by debris flows—typically to bedrock—is the dominant disturbance process, controlling channel incision and downstream transport of sediment (Benda, 1990; Seidl and Dietrich, 1992; Montgomery and Buffington, 1997) and wood (Benda and Sias, 1998) as well as riparian vegetation disturbance. The frequency of debris flows is much greater in 1st-order channels than in hollows due to numerous potential upslope source areas (Reneau and Dietrich, 1987). For a subset of the study area used in this investigation, Swanson et al. (1982a) estimated that debris flows in 1st-order channels draining small (~10 ha) watersheds have average recurrence interval of approximately 580 years.

Farther downstream, steep, low-order perennial tributaries whose channels are confined within narrow valleys may also be subject to relatively infrequent but severe disturbance by debris flows originating upstream. These channels—corresponding to cascade and step-pool channel types *sensu* Montgomery and Buffington (1997)—generally have a stepped longitudinal bed profile. Step-pool channels typically have two thresholds of bed mobility, with relatively frequent transport of finer (sand/gravel/cobble) bed material during moderate peak flows and infrequent transport of large step-forming or framework particles (Ashida et al., 1981; Grant et al., 1990; Schmidt and Ergenzinger, 1992; Montgomery and Buffington, 1997). They are transitional between debris-flow dominated colluvial channels and fluvially dominated mainstem channels.

Within the main valley bottoms, relatively low-gradient (≤ 4% slope, roughly speaking) mainstem channels (corresponding to plane-bed, pool-riffle, or braided channel types in Montgomery and Buffington's [1997] classification system) are dominantly shaped by fluvial disturbance processes. Mainstem channels can be laterally constrained within bedrock gorges or by earthflows, tributary alluvial fans, terraces, or other valley-bottom landforms, or they may be unconstrained floodplain channels occupying wide valley bottoms (Grant and Swanson, 1995). In either case, bed mobility is predicted to be greater than in the steep tributary channels. However, Grant and Swanson (1995) report greater frequency of large boulders and greater channel roughness in constrained reaches, which may indicate greater channel stability relative to unconstrained reaches. Unconstrained mainstem channels are characterized by more extensive off-channel and hyporheic habitat than constrained channels and by greater lateral channel mobility (e.g., multiple channels, channel migration, channel avulsion), suggesting that they should be more dynamic than constrained reaches.

8.2 Cross Section Sampling Design

Long-term reference cross section monitoring sites were established at five locations in the Andrews Forest between 1978 and 1981 (Figure 3.1) and have been monitored at intervals of one to two years since establishment. The hierarchically nested sampling design of the cross sections (Figure 8.3)—five sites arrayed within a single watershed along a gradient of channel size (2nd to 5th- order channels) with multiple cross sections at each site arrayed along the channel at intervals of one to several channel widths—allows them to be used to assess channel changes over time at a range of spatial scales, ranging from the watershed scale (comparisons between sites) to the reach scale (individual cross section sites) to finer scales (sets of adjacent cross sections or changes within individual cross sections). In particular, they can be used to characterize channel response to floods across a range of flows (i.e., over the range of sizes of the largest peak flow between consecutive surveys) at each site (reach scale) and to compare these responses between sites located in different portions of the drainage network. The cross section data can thus be tested against

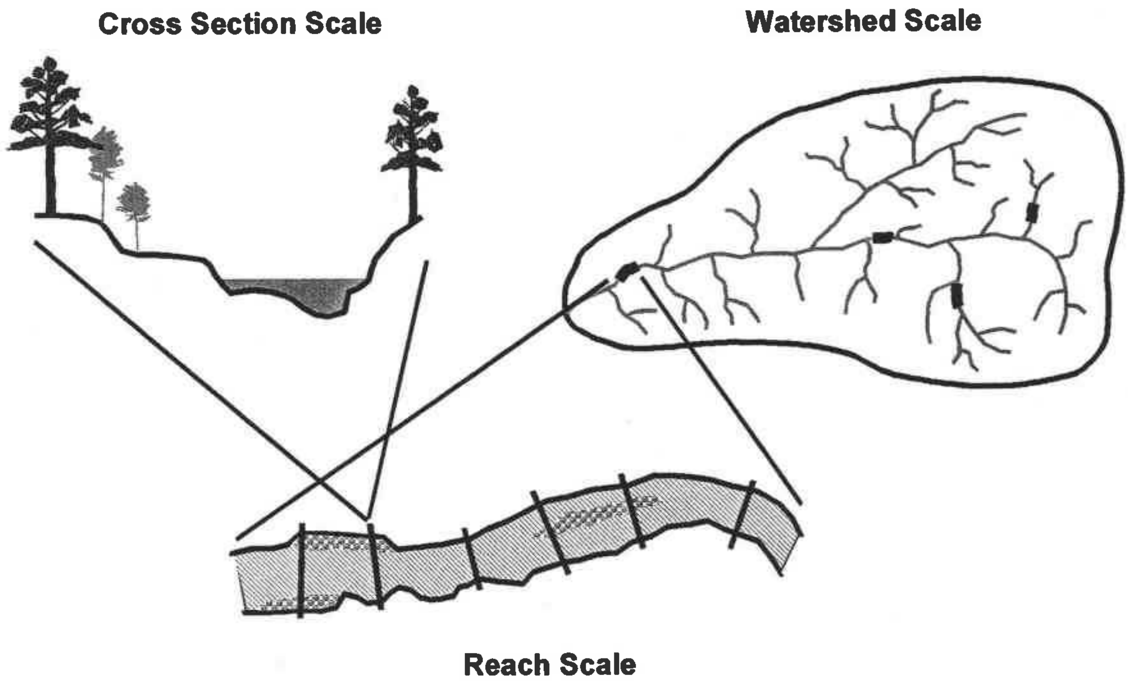


Figure 8.3. Schematic diagram showing nested cross section sampling design

predictions of the PDC and other hypotheses about watershed scale spatial patterns of channel dynamics, although the small number of sites and the lack of replication precludes any statistical hypothesis testing at this scale.

8.3 Styles of Channel Response Inferred from Cross Section Changes

A variety of different styles of channel adjustment can be inferred from changes in the cross section profiles (Figure 8.4). A lowering of all or a part of the streambed is classified as scour or degradation (Figure 8.4[a]), while an increase in the bed elevation within all or a portion of the channel due to deposition within the channel is classified as fill or aggradation (Figure 8.4[b])[1]. A combination of both significant scour and fill within a single cross section (Figure 8.4[c]) is a common response that may reflect complex channel adjustments, such local scour and fill

[1] The terms aggradation and degradation are typically reserved for changes that affect the entire bed of at least the perennially wetted portion of the channel (i.e., the low flow channel), and are used in that sense here.

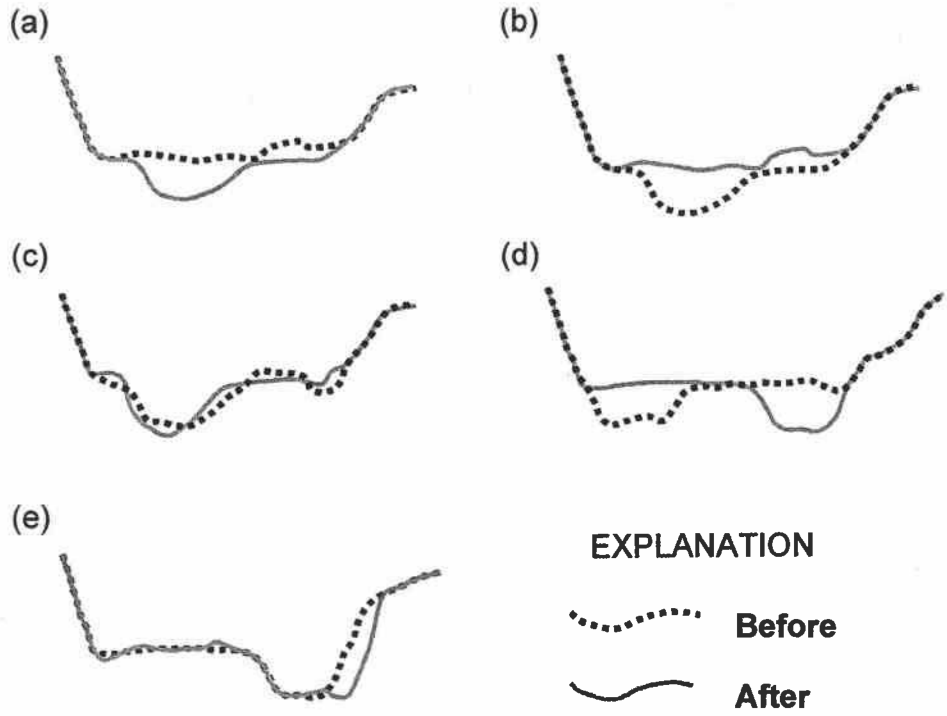


Figure 8.4. Styles of channel response inferred from hypothetical cross section profile changes: (a) degradation or scour, (b) aggradation or fill, (c) mixed scour and fill, (d) lateral channel shift, and (e) bank erosion.

around a large log or deepening of the channel thalweg accompanied by deposition on or lateral accretion of an adjacent lateral bar. A lateral channel shift (Figure 8.4[d]) also typically involves both scour and fill within a single cross section, but is distinguished by the creation of a new low flow channel with or without filling in of the previous channel thalweg. Bank erosion is distinguished by a lateral retreat of the bank (Figure 8.4[e]), but excludes lateral channel erosion within the floodway. For the purposes of this study, the bank, or edge of the active channel floodway, was distinguished on the basis of topography and a transition from a recent alluvial substrate (e.g., cobble, gravel, etc.), indicating periodic disturbance by high energy flood flows, to a soil-covered surface with terrestrial vegetation.

8.4 Conceptual Model for Reach Scale Channel Response

In a generic sense, the response of a stream channel to a flood or peak flow event at the reach scale can be quantified in at least three ways: (1) as the probability of observing a measurable response exceeding some threshold criterion at a particular point in space, (2) as the proportion of the stream channel length or area reworked or altered over a specified reach, or (3) as some measure of the magnitude of response, such as volume of sediment per unit stream length reworked (scoured and/or deposited). The first two measures are equivalent if the probability of response is independent of location, since if a particular flood reworks x percent of the stream channel in a randomly distributed fashion, then the probability of observing a change at a randomly chosen point within the stream channel is also x percent. Thus, we have two types of measures of channel response: probability of response and magnitude of response. The core historical data set used in this study, repeated surveys of sets of 11 to 20 cross sections at fixed locations within five reference reaches, can be used for either type of measurement, and both types were used in this study.

Figure 8.5 presents several hypothetical channel "response curves," in which the measure of channel response (plotted on the y axis) is the probability of observing change that exceeds some response criterion (e.g., a detection limit or an arbitrarily specified value) at a randomly selected cross section location (or, equivalently, the proportion of cross sections within a reach that exhibit such changes). The independent variable driving the response (plotted on the x axis) is a measure of flood magnitude, such as the maximum instantaneous peak unit area discharge, Q^*,[2] for the time period between successive observations (i.e., cross section surveys). Thus, the response curve specifies, for any value Q^*_p of Q^*, the probability p that some measure of channel change, Δ, exceeds a detection limit or other specified value, δ_0. We can write this mathematically as

$$p = \Pr\{\Delta \geq \delta_0 \mid Q^* = Q^*_p\} \qquad (8.1)$$

[2] Unit area discharge is the discharge at a point divided by upstream drainage area, which is an appropriate measure for peak flows that are to be compared across a range of stream sizes. Alternatively, the independent variable driving the response could be some measure of applied stress derived from the peak flood discharge, such as peak average boundary shear stress acting on the bed.

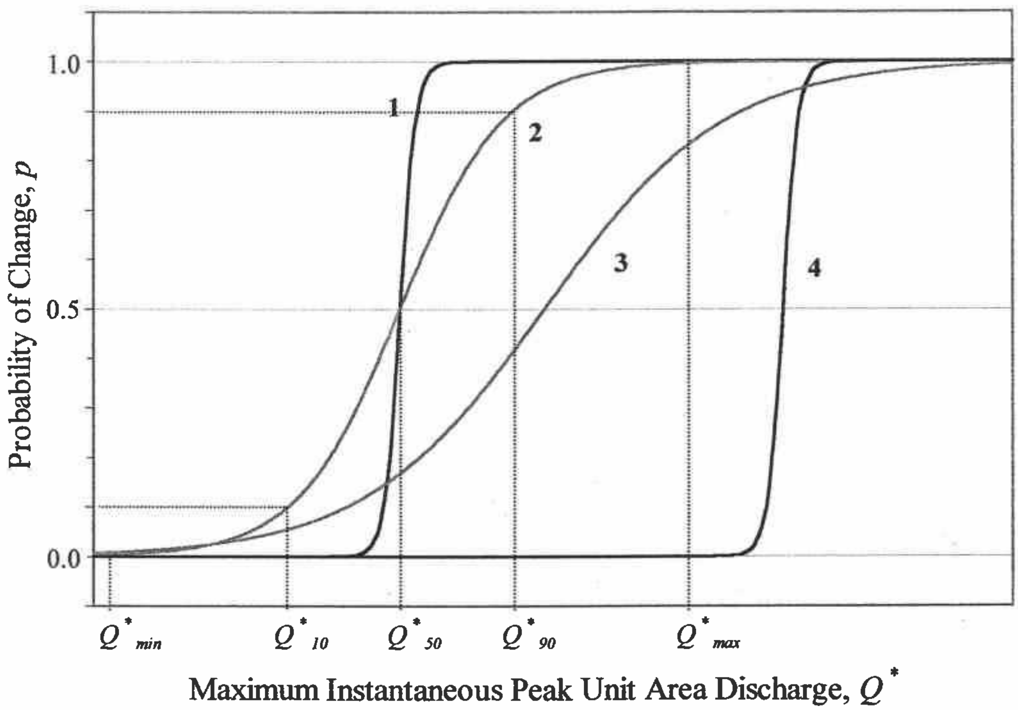


Figure 8.5. Hypothetical channel response curves showing probability of observing a change in channel cross sectional profile as a function of increasing maximum peak instantaneous discharge for the period between consecutive observations. Labeled values of Q^* (Q^*_{min}, etc.) refer to curve 2. Q^*_{min} represents the value of Q* below which there is a neglible chance of observing change, while Q^*_{max} represents the value of Q^* above which channel change is essentially certain. Q^*_{xx} denotes the value of Q^* associated with an *xx* percent probability of observing channel change at a randomly selected location in the hypothetical stream reach represented by curve 2.

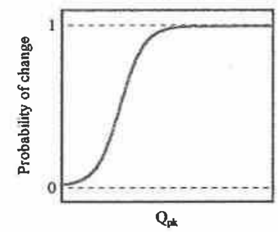
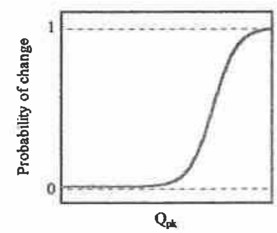
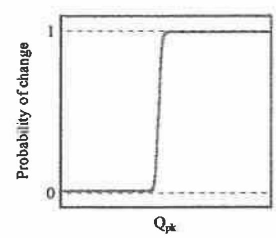
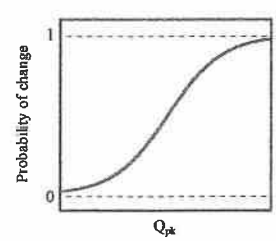
where the change measure, Δ, is treated as a random variable that is some unknown function of Q^*.

Let us assume that the probability of observing a response will be essentially zero for very low values of Q^* and essentially one for very high values of Q^*. That is, we assume that there is some lower limit on discharge below which detectable channel changes never occur and some upper limit above which detectable changes always occur. These limits—call them Q^*_{min} and Q^*_{max}, respectively (see Figure 8.5)—bracket the rising limb of the response curve, which is the part that characterizes the nature of the channel response. In comparing the response of two stream reaches, two characteristics of the response curve that are of particular interest are the slope and position along the x axis of this rising limb. The slope determines how gradually or abruptly the probability of channel adjustment increases with increasing discharge above Q^*_{min}. If the slope is low ($Q^*_{max} >> Q^*_{min}$), the increase in response probability is gradual and may be approximately linear over a fairly wide range of discharge (e.g., curve 3 in Figure 8.5). At the opposite extreme, if the slope of the rising limb of the response curve is very steep, the response curve can become almost a step function (Figure 8.5, curves 1 and 4), indicating a threshold-type response in which a small incremental increase in Q^* is associated with a very large increase in the probability of a response being observed. Since the response probability p may never actually equal zero or one but only asymptotically approach these values, it may be more useful in practice to replace Q^*_{min} and Q^*_{max} with values of Q^* corresponding to specified probabilities values of p—say, 10% and 90%, or Q^*_{10} and Q^*_{90}, respectively (Figure 8.5).

The lateral position along the x axis of the rising limb of the response curve characterizes the relative resistance of the channel to disturbance. A logical choice as a measure of this property for comparing channels whose response curves may have different slopes (e.g., curves 1 and 2 or 3 and 4 in Figure 8.5) is the value of Q^* corresponding to a 50% probability of change (i.e., the midpoint of the rising limb), or Q^*_{50} (Figure 8.5). However, it may also be instructive to compare the values of Q^* for different reaches corresponding to other specified response probabilities. For example, Q^*_{10} may be thought of as representing the peak flow magnitude at which mobilization of the bed begins to occur, while Q^*_{90} may be interpreted as the minimum peak flow magnitude required for widespread reworking of the channel bed.

Within this framework, the response of a channel may be characterized as either threshold-like or gradual and as exhibiting either a low or high resistance to disturbance (Figure 8.5). Two reaches may both exhibit clearly defined thresholds but at different values of Q^*_{50} (Figure 8.5, curves 1 and 4), or they may exhibit the same overall resistance to disturbance (same Q^*_{50}) but differ in the degree to which they express threshold-like or gradual response behavior (e.g., Figure 8.5, curves 1 and 2).

Table 8.1. Relationship between channel attributes at the cross section to reach scale and expected channel response characteristics

Channel Response Characteristic	Cross Section/Reach Attributes	Response Curve
Low resistance to disturbance	- fine particle size - few large roughness elements[1] - low bedform resistance - plane-bed or pool-riffle channel type[2]	
High resistance to disturbance	- coarse particle size - bedrock or resistant bed/banks - abundant large roughness elements[1] - high bedform resistance - cascade or step-pool channel type[2]	
Well defined response "equal mobility"	- homgeneous particle size distribution - few large roughness elements[1] - relatively uniform channel width - relatively uniform channel gradient	
Poorly defined response 'selective transport'	- patchy particle size variations - abundant large roughness elements[1] - locally variable channel width - locally variable channel gradient	

Notes:

[1] very large boulders, large logs, etc.

[2] per channel classification scheme of Montgomery and Buffington (1997)

Alternatively, the response of the reaches may differ in both respects, as is the case for curves 3 and 4 in Figure 8.5.

Table 8.1 presents a conceptual model of channel response to peak flows based on these channel response characteristics—i.e., low vs. high resistance to disturbance and abrupt (threshold-like) vs. gradual response to increasing peak flow magnitude. For each response characteristic in column 1, column 2 lists channel attributes at the scale of the reach to the individual cross section that are hypothesized to give rise to that response behavior. The third column in Table 8.1 shows a sample response curve of the type that would be expected for a channel with the indicated attributes.

Certain channel characteristics are expected to contribute to low or high resistance to disturbance by peak flows. Low resistance to disturbance is hypothesized to be associated with relatively finer particle size, few large roughness elements such as very large boulders or logs, and low bedform resistance—in other words, with low hydraulic roughness (Table 8.1). Channel types characteristic of "response" segments in the Montgomery and Buffington (1997) classification scheme (i.e., plane-bed, pool-riffle, and dune-ripple channels) would be expected to have these attributes and, hence, to exhibit relatively low resistance to disturbance. At the channel unit scale, pools would be expected to exhibit more frequent changes than other channel unit types (i.e., riffles, rapids, cascades, or steps), since they are characterized by generally finer particle size and lower relative roughness (Grant et al., 1990), and since pools may act as temporary storage sites for finer bed material than that which comprises the channel bed generally (Lisle and Madej, 1992).

On the other hand, high resistance to disturbance is expected for channels having bedrock or other resistant bed/bank material and/or high hydraulic roughness characterized by relatively coarser particle size, abundant large roughness elements, and/or high bedform resistance (Table 8.1). Channel types characteristic of "transport" segments (i.e., bedrock, cascade, or step-pool channels; Montgomery and Buffington, 1997) tend to have these attributes and hence would be expected to exhibit relatively high resistance to disturbance.

Certain channel characteristics also are expected to promote either a well-defined threshold of channel response or, alternately, a more gradual increase in the degree of channel response with increasing discharge. A well-defined response threshold might be expected to be associated with a relatively homogeneous channel characterized by a narrow range of particle sizes comprising the bed, few large roughness elements, and relatively uniform channel width and gradient (Table 8.1). However, some field and laboratory based studies have suggested that even in a bed of mixed particle sizes, particles of all sizes may be entrained over a narrow range of flow conditions due to the greater exposure of larger particles that protrude from the bed, "hiding" of smaller particle by larger ones, or the development of a surface pavement of relatively uniform size that regulates the transport of finer, more heterogeneous bed material (Parker et al., 1982; Andrews, 1983; Wilcock and Southard, 1988). This "equal mobility" hypothesis is consistent with a threshold type channel response.

In contrast, a poorly defined response threshold is hypothesized to be associated with relatively heterogeneous bed material particle size, abundant large roughness elements, and local variations in channel width and gradient. Heterogeneous particle size should lead to a more gradual reach scale channel response with a poorly defined response threshold (bottom row in Table 8.1) under certain conditions. These include selective transport of different particle sizes (e.g., Komar, 1987; Shih and Komar, 1990a, 1990b), which may be enhanced by spatial variability in local hydraulic conditions and sediment mobility resulting from heterogeneity at scales larger than the individual particle (e.g., sediment patches, bedforms, large logs, variations in channel width, etc.).

8.5 Study Design

This study used a combination of historical monitoring data, additional field work to characterize the long-term cross section references sites, and a variety of analytical approaches in pursuit of the research objectives set forth in Chapter 1. Major components of the study included the following:

1. Study site characterization,
2. Peak flow analysis,

3. Statistical analysis of observed probabilities of channel cross section response probability in relation to peak flow magnitude, and
4. Descriptive analysis of channel and riparian response to two large floods, with an emphasis on differences between tributary and mainstem streams.

First, study site characterization field work was undertaken to map the position of the cross sections relative to each other and to channel features, and to provide a geomorphic context for each site. Second, an analysis of historical peak flow data from stream gaging stations within the study area was performed to characterize the magnitude, frequency and recurrence intervals for the peak flow events driving the channel responses observed at the reference cross sections. In the third component of the study, logistic regression was used in conjunction with a classification-based analysis of the cross section data to assess the relationship between peak flow magnitude or recurrence interval and the proportion of cross sections at a site exhibiting a detectable response. These results were used to infer the frequency of specified levels of relative channel disturbance at four of the cross section sites. The fourth component of the study inferred differences between low-order tributary sites and mainstem sites in the style and degree of disturbance caused by a moderately large flood (6- to 12-year recurrence interval) in 1986 and a major flood (25 to 100+ year recurrence interval) in 1996 using quantitative measures of the magnitude of channel response at the cross section sites as well as qualitative observations of flood effects.

9 Study Area and Methods

This chapter describes the study area and the field and analytical methods employed in this study. Section 9.1 describes the study area and the physical characteristics and geomorphic setting of the cross section sites. Section 9.2 describes the historical data sets used and issues pertaining to data collection methods for the cross section data set in particular. Methods employed by the author in conducting supplemental field investigations at the cross section study sites are described in Section 9.3. Section 9.4 details how the historical cross section data were prepared for analysis, including error checking and quality control measures and corrections and adjustments applied to the data. Data preparation for mapping and surveying is described in Section 9.5. Finally, methods used to analyze peak flow data and cross section changes are presented in Sections 9.6 and 9.7, respectively.

9.1 Study Area

9.1.1 H.J. Andrews Experimental Forest

The H. J. Andrews Experimental Forest (Andrews Forest) occupies the 5th-order, 64 km^2 watershed of Lookout Creek located, at the eastern edge of the Western Cascades in the Willamette National Forest, Oregon (Figure 3.1). The elevation range in the watershed is 410 to 1630 m. Approximately three-quarters of the watershed is forested with 100- to 500-year old stands dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and by western redcedar (*Thuja plicata*) at lower elevations and by Pacific silver fir (*Abies amabilis*) at upper elevations. Approximately 20% of the watershed was harvested from 1950 to 1970, and a further 5% was harvested by 1990 (Jones and Grant, 1996). Annual precipitation ranges from approximately 2300 to 3500 mm, depending on elevation, over 80% of which falls from November through April. Rain-on-snow events in the "transient snow zone" between 400 and 1200 m are a major factor in generating most large floods in the Andrews (Harr, 1981; 1986), including the December 1964 and February 1996 floods, the largest on record in the watershed.

Glacial, fluvial, and mass movement processes have all played important roles in shaping the current landscape of the Andrews Forest (Swanson and James, 1975a, 1975b). The Forest is underlain by bedrock consisting principally of volcaniclastic rocks and lava flows of late Oligocene to Pliocene age, intruded in the lower part of the basin by northwest to southeast-trending dikes (Peck et al., 1964; Swanson and James, 1975a; Priest et al., 1983). The volcaniclastic rocks tend to be deeply weathered, and the landscape is deeply dissected. Glacial deposits are found in the upper part of the Lookout Creek watershed, extending down to at least 1 km downstream of the Mack Creek confluence (Figure 3.1) and to the 2,500-foot (760 m) elevation along McCrae Creek (Swanson and James, 1975a). A fluvial terrace 5 to 8 m above the present channel occurs along the lower 4 km of Lookout Creek; this terrace was abandoned at least 7,000 years ago based on the presence of deposits Mazama ash on its upper surface. The current channel is incised into the terrace and into inactive alluvial fans (also pre-Mazama ash) deposited on the terrace and lower floodplain survaces (Swanson and James, 1975a, 1975b). A wide segment of valley floor (300 to 400 m across), underlain by alluvial sediments, extends from a point 5 km upstream of the mouth of Lookout Creek to about 1 km downstream of the Mack Creek confluence, a distance of about 4.5 km (Figure 3.1). This feature is the result of deposition before mid-Holocene time upstream of a channel constriction caused by a massive, now inactive, earthflow (Swanson and James, 1975a).

Both slow, deep-seated earthflows and rapid, shallow mass movements (debris slides and debris flows) are important processes within the Andrews Forest. Both types of mass movements occur predominantly in areas underlain by deeply weathered volcaniclastic rocks, particularly where these are overlain by more resistant lava flows (Swanson and James, 1975a). A majority of the documented debris flows within the Andrews Forest during the past 50 years (Figure 9.1) have been observed at elevations of between 600 and 800 m, where this transition from weak to resistant bedrock occurs (Dyrness, 1967; Swanson and James, 1975b; Snyder, in preparation).

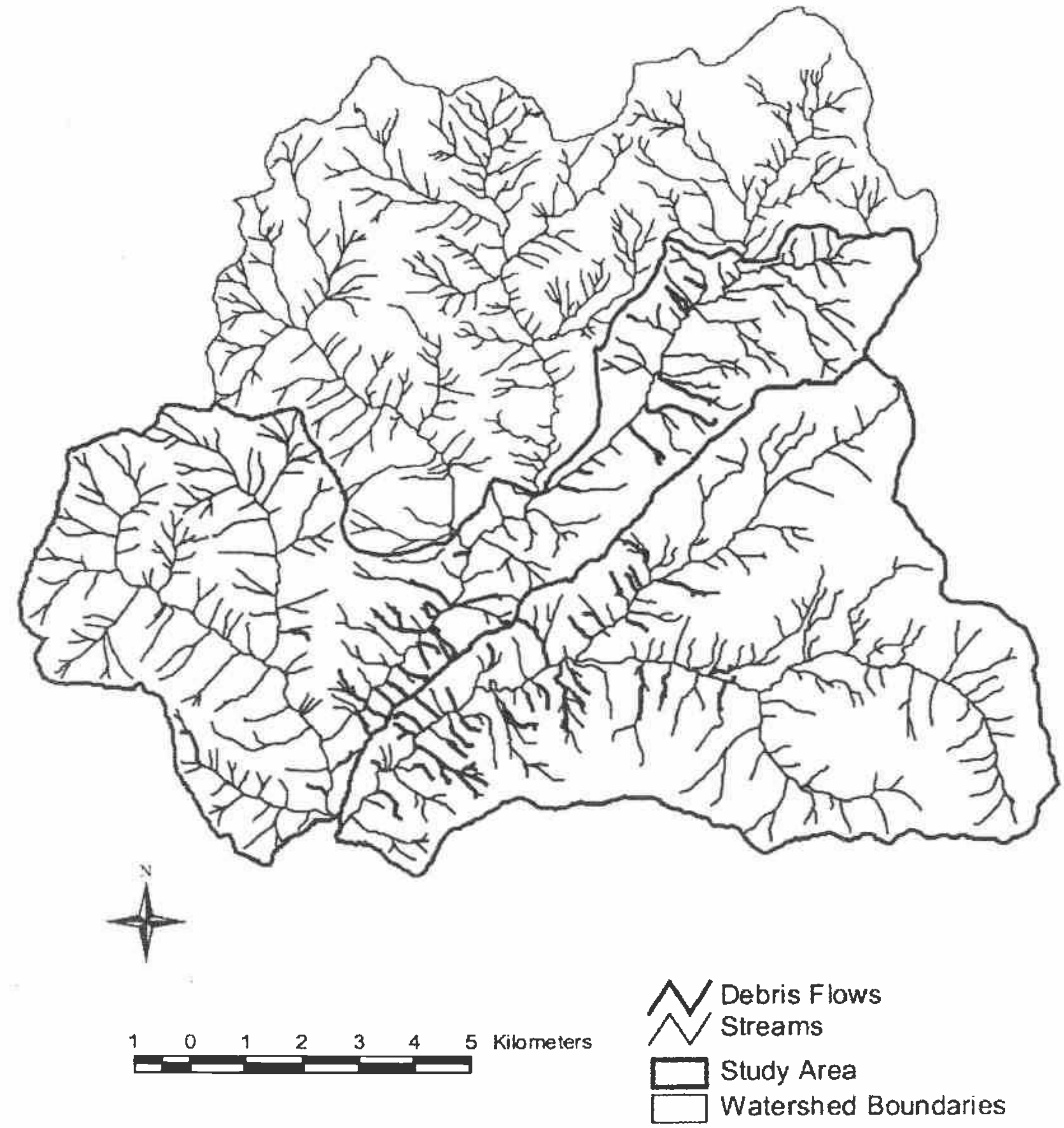


Figure 9.1. Locations of known debris flows in the Lookout Creek watershed and a portion of the Upper Blue River watershed, 1946-1996. (Source: Snyder, in preparation)

Table 9.1. Cross section site characteristics.

Site		COC	MAC	MCC	LOM	LOL
No. of cross sections		17	12	20	11	14
Drainage area, km^2		0.71	5.6	5.9	31.7	61.5
Elevation at lower end, m above msl		~ 1000	766	734	~ 575	~ 435
Avg. channel slope		0.168	0.100	0.096	0.032	0.015
Avg. channel width, m		5.3	13.0	10.7	24.7	27.3
Reach length, m		170	230	230	300	470
Reach length: avg. channel width		32.1	17.7	21.5	12.1	17.2
Bed surface particle size in mm (1995 data)	D_{84}	301	302	230	305	234
	D_{50}	95	77	57	147	100
	D_{16}	20	17	14	38	30
Degree of channel constraint		high	high	high-mod.	low	high-mod.
Adjacent forest type[(1)]		old-growth	old-growth	young conifer	old-growth, mixed	old-growth, young
Abundance of in-channel CWD		high	high	low	mod.	low

[(1)] old-growth = conifers > 200 yr; young conifer = conifers < 40 yr (plantation); mixed = mature mixed conifer & hardwood forest

The following sections describe the general characteristics and geomorphic setting of the individual cross section sites. The five cross section sites (reaches) can be viewed as being arrayed along a hydrologic and geomorphic gradient from the headwaters (Cold Creek site) to the mouth (lower Lookout Creek site) of the Lookout Creek watershed. Along this gradient, drainage area and channel width systematically increase, while channel slope systematically decreases. Other characteristics—such as the abundance of LWD and the degree to which the channel is constrained laterally by valley walls, terraces, or other non-fluvial or relict landforms—vary in a less systematic fashion (Table 9.1).

9.1.2 Cold Creek

The Cold Creek (COC) site is a high elevation (1000 m) headwaters channel with a drainage area of approximately 71 ha (0.71 km^2; Table 9.1). While Cold Creek likely experienced some degree of past glaciation, the study reach is narrow (5.3-m average channel width), highly constrained by valley sidewalls, and quite steep (average gradient of 17%). The channel contains abundant woody debris (Figure 9.2), but most of the larger pieces and the majority of the volume of LWD is suspended well above the channel bed. The longitudinal profile of the channel has a decidedly stepped appearance, with most of the fall occurring as boulder or log steps. The channel would be classified as a cascade channel type in the Montgomery and Buffington (1997) classification scheme.

The reference reach contains 17 cross sections, labeled XS 1 to XS 17, with numbers increasing upstream (Figure 9.3). The lowermost cross section is located approximately 50 m upstream of Forest Road 1506, the main access road into the Andrews Forest, and the uppermost cross section is located approximately 170 m farther upstream.

The channel contains many large boulders and logs (Figures 9.2 and Appendix C, Figures C.1 through C.6) which appear to be immobile under the current hydrologic regime, at least with respect to purely fluvial transport processes. Even small boulders and larger cobbles are typically moss-covered, indicating lack of recent transport.

Figure 9.2. View of channel at the Cold Creek (COC) cross section site.

However, pools and other low-gradient channel units between longitudinal steps contain a substantial amount of gravel- to cobble-sized sediment (as well as minor sand) which appears to be actively transported.

While the canyon drained by Cold Creek is narrow, its floor and lower sidewalls exhibit a distinctly trough-shaped cross-section, which may be the result of repeated scour by debris flows. Within this U-shaped trough are small (several m^2 to several tens of m^2), low (0.25-0.5 m above the low flow water surface) floodplain-like surfaces adjacent to the channel, which in at least some instances appear to have been formed by slumping of the valley sidewalls. Vegetation on these surfaces showed no sign of disturbance following the major flood of February 1996. The absence of large trees adjacent to the channel within the U-shaped trough (despite the lack of evidence of any recent disturbance) suggests that the channel may have experienced debris flows within recent decades. However, debris flow surveys conducted in the Andrews Forest in the 1960s, 1970s and 1990s show no evidence of debris slides or debris

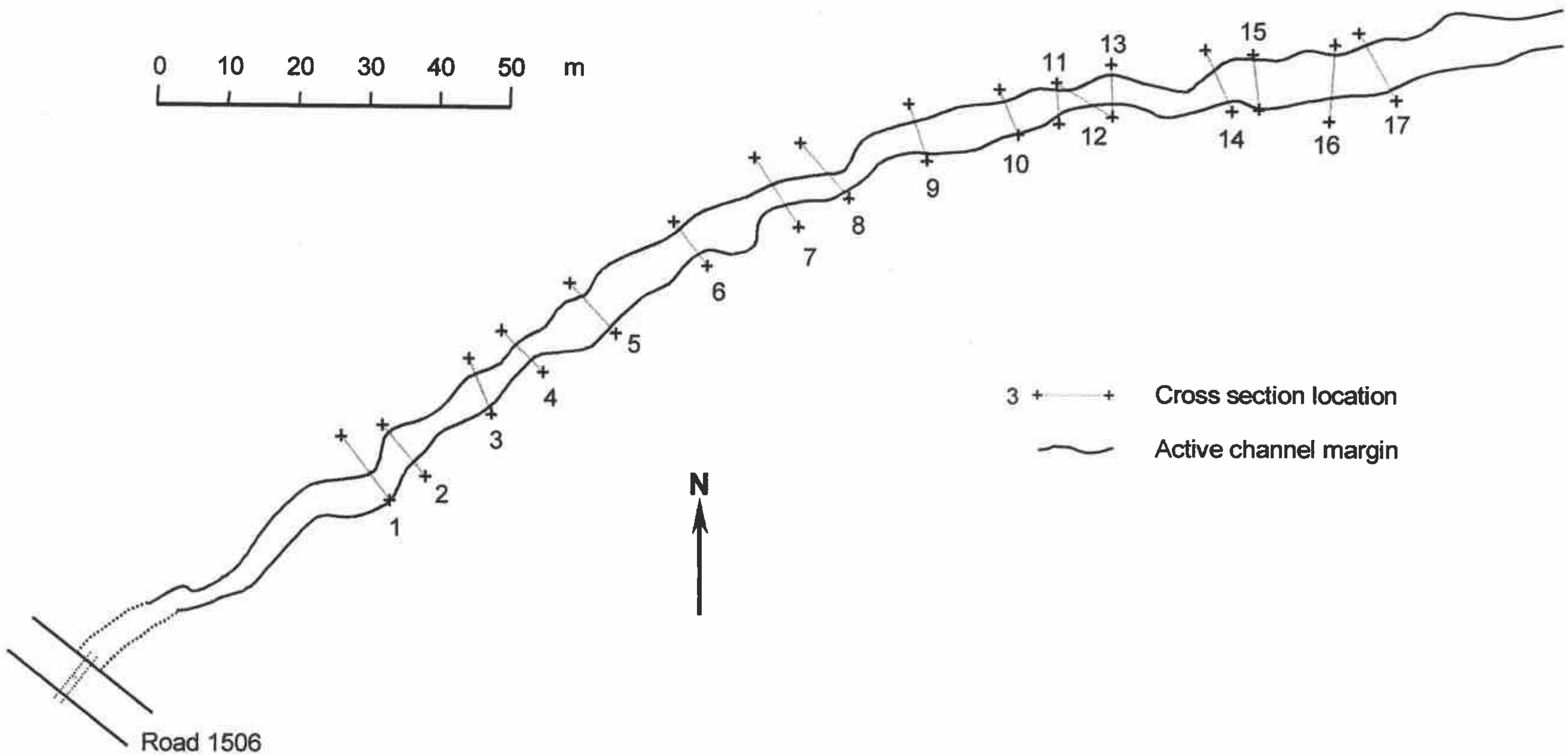


Figure 9.3. Map of Cold Creek (COC) site showing cross section locations.

flows in this part of the watershed and none originating above an elevation of approximately 3500 ft (1070 m); most have occurred between elevations of 2000 and 2600 ft (600 to 800 m) (Dyrness, 1967; Swanson and James, 1975b; Snyder, in preparation).

Cold Creek is the only 2nd-order tributary in which long-term cross section monitoring has been conducted, but it is quite different from the better studied, low elevation small watersheds of similar size (WS 1, 2 and 3, Figure 3.1), which have produced documented debris slides and debris flows. The latter streams are probably more representative of "typical" low-order streams in the western Cascades, particularly those located in areas affected by timber harvest.

9.1.3 Mack Creek Old-growth and Clearcut Sites

The Mack Creek old-growth (MAC) and clearcut (MCC) sites are nearly adjacent, contrasting 320-m long reaches at the downstream end of the undisturbed portion of the Mack Creek watershed (Figure 3.1). The MAC reach flows through old-growth forest in which Douglas fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*) form a nearly closed canopy over the stream channel. Bigleaf maple (*Acer macrophyllum*) also grow within the riparian zone. Woody debris is abundant within the channel, including many logs greater than 75 cm in diameter and a few as large as 1.5 m in diameter (Figure 4.3). Unlike Cold Creek, a majority of these logs rest on or partially on the channel bed rather than being suspended above the channel, due to the wider channel and valley floor. Many of the pieces less than 10 m in length have been fluvially transported at least some distance, and much of the LWD is concentrated into accumulations which span part or all of the channel (Figure 4.3). Within the MAC reach, there are two log steps and one large channel-spanning LWD accumulation (LWD jam); a second large LWD jam occurs just upstream of the uppermost MAC cross section (XS 12; Figure 9.4).

In contrast, the slopes adjacent to the channel at the MCC site were clearcut in 1964-65, and the reach contains very little woody debris and essentially no large logs

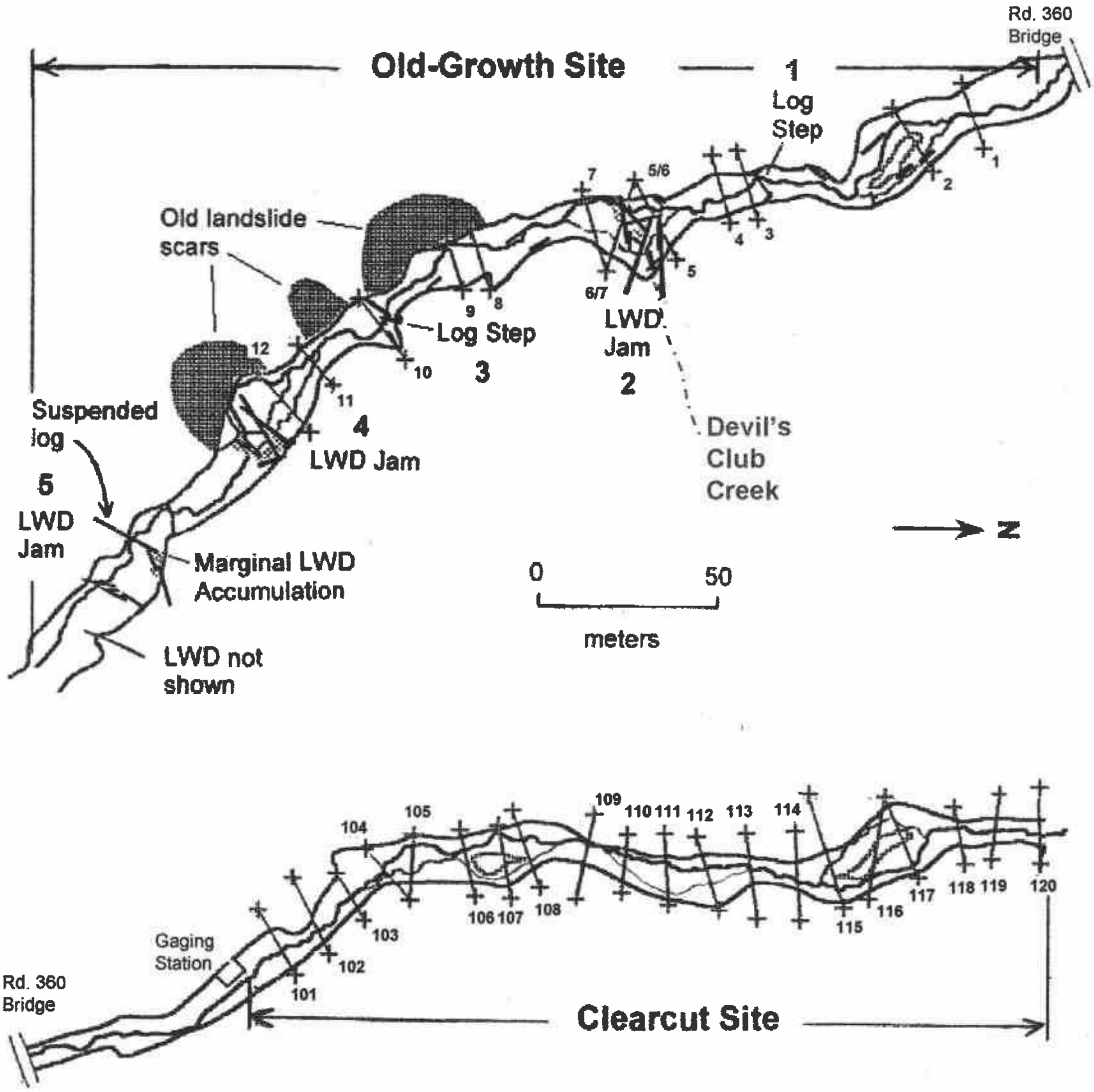


Figure 9.4. Map showing selected channel features and cross section locations at the Mack Creek old-growth (MAC) site, top, and the clearcut (MCC) site, bottom. Downstream is toward the right.

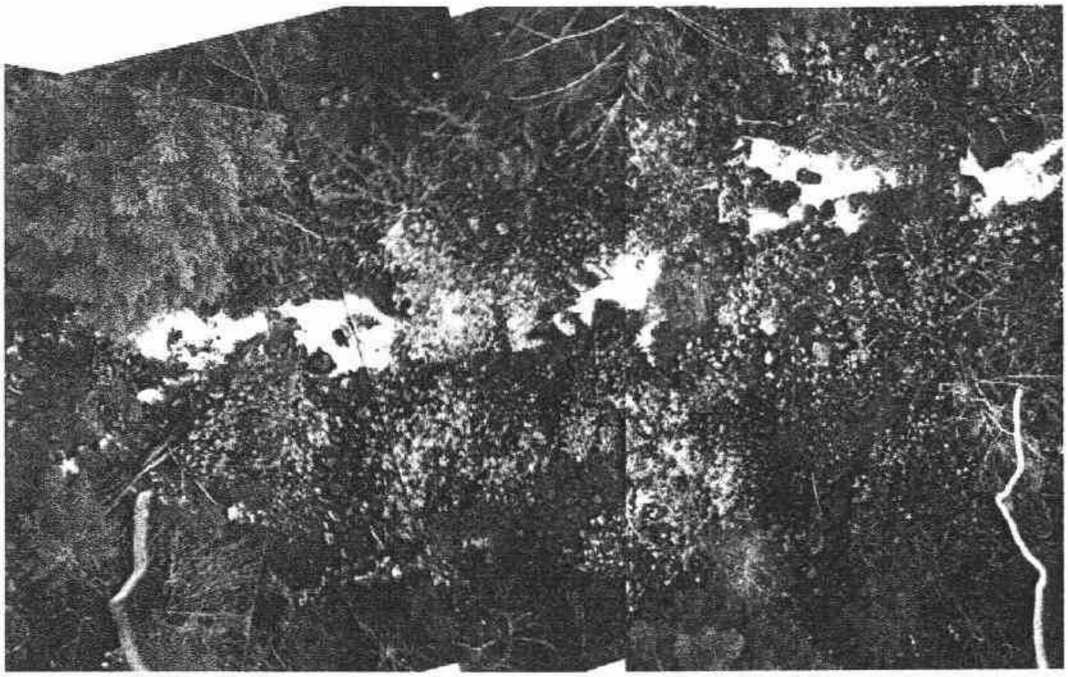


Figure 9.5. Aerial view of a portion of the Mack Creek clearcut (MCC) reach. Note steep, step-pool configuration of main channel. Side channel at bottom of photo, separated from main channel by a willow-covered bar, is active at this moderate fall flow.

(Figure 9.5). LWD was removed from the channel during the logging operation and by a major flood in December 1964, and regrowth on the streambanks and adjacent hillslopes is not yet capable of supplying much LWD to the channel. Inputs of LWD from the upstream reach (particularly large pieces) were effectively blocked by a culvert at the road crossing at the downstream end of the old-growth site prior to removal of the culvert and its replacement by a bridge in September 1994.

The old-growth reach contains 12 cross sections which are numbered XS 1 through XS 12 in the upstream direction; the lowermost (XS 1) is located approximately 30 m upstream from the bridge (Figure 9.4). The clearcut reference reach contains 20 cross sections, assigned 3-digit numbers (XS 101 through XS 120) that, contrary to the old-growth reach, increase in the *downstream* direction (Figure 9.4). The uppermost MCC cross section is located approximately 75 m downstream of the road crossing.

The Mack Creek gaging station (Figure 9.4) is located at the upstream end of the clearcut reach. The gaging station flume creates an abrupt drop of over 2 m—in essence, an artificial waterfall—less than 15 m upstream of XS 101 (Figure 9.4). The elevation and drainage area for this station are 758 m and 5.81 ha (5.81 km^2), respectively. Drainage areas at the downstream ends of the old-growth and clearcut reaches, estimated from 30-m DEM, are 5.6 and 5.9 km^2, respectively (Table 9.1). Average channel width is approximately 13 m for the old-growth reach and approximately 11 m for the clearcut reach, but the width is quite variable in both reaches. Average channel gradient was estimated from the longitudinal profile survey to be 10.0% for the old-growth reach and 9.6% for the clearcut reach.

The old-growth reach is fairly tightly constrained by adjacent hillslopes, particularly along the left bank, where there are several landslide scars in which large trees are absent and bedrock is exposed (Figure 9.4). The right bank is generally less steep and lacking in bedrock. Much of the right bank is bordered by a high, terrace-like landform, possibly residual glacial deposits. A 1st-order tributary informally named Devil's Club Creek enters from the right between XS 5 and 6. The tributary is incised into antecedent alluvial fan deposits. Bedrock is also exposed sporadically in the channel bed and banks within the old-growth reach, particularly where flow is directed against the bank as in the vicinity of XS 12 and XS 8 and 9 on the left bank (all of which are located at the foot of landslide scars, Figure 9.4) and at the sharp left bend in the channel between XS 2 and 3. However, most of the bed within the old-growth reach is covered with alluvial sediment, even in areas with bedrock banks.

However, extensive areas of bedrock are exposed in the channel bed between the bridge and the upper end of the clearcut reach, especially within a narrow (7-m wide) boulder-armored section extending about 25 m downstream from the bridge. This boulder-armored channel was constructed in the summer of 1994, when the 10 ft (3 m) diameter, 75 ft (23 m) long culvert pipe previously at the road crossing was removed to improve fish passage. Approximately 1200-1500 yd^3 of sediment were excavated at that time (Cissel, personal communication). Bedrock is also exposed in the channel bed within the two uppermost MCC cross sections (XS 101 and 102), but was not present at this location prior to the 1996 flood. No bedrock is exposed within the bed or banks of the clearcut reach downstream of XS 102, nor was any observed between the downstream end of the clearcut reach and the confluence of Mack Creek with Lookout Creek—a distance of approximately 700 m—during a reconnaissance trip in the summer of 1997.

The clearcut reach is somewhat less tightly constrained by the adjacent hillslopes than the old-growth reach. Low areas that appear to be abandoned channels choked with logging debris occur alternately on the right and left sides of the active channel, but the debris and dense vegetation typical of regrowth in clearcuts made detailed mapping of these features impractical. Other than some sand and some possibly rafted deposits of small organic debris, there was little evidence of much recent activity in these suspected former channels.

The riparian zone within the clearcut reach contains abundant willow (*Salix spp.*) along the channel margins and on mid-channel bars, as well as some vine maple (*Acer circinatum*) and mature red alder (*Alnus rubra*). The channel exhibits a bit of a tendency to bifurcate within this reach. Secondary channels active only during moderately high flows are present along the right channel margin in the vicinity of XS 106 to 108 and XS 110 to 112, separated from the main channel by a low surface vegetated with willow and alder (Figure 9.5). Farther downstream, two channels of nearly equal width (the left channel being somewhat higher and hence not active at very low flows) are present between XS 115 and 117 (Figure 9.4); these channels are separated by a willow-covered bar with one or two mature alders at the downstream end.

Upstream of the road crossing, Mack Creek drains the largest uncut portion of the Andrews Forest. Its forest cover, due to the north-facing aspect, has experienced no fires in 450+ years and is unusually rich in old-growth relative other uncut areas of the Andrews (Weisberg, 1998). Hence, the MAC site is unique within the Andrews Forest and probably has few analogues in the Western Cascades. The MCC site, in contrast, may be more representative of many 3rd-order streams on public forest land today.

9.1.4 Middle Lookout Creek Site

The middle Lookout Creek (LOM) site consists of 11 irregularly spaced cross sections in a 300-m long reach (Figure 9.6). It is located roughly in the middle of the Lookout Creek watershed on 4th-order Lookout Creek (Figure 3.1) at an elevation of approximately 575 m. The upper of two low elevation mainstem Lookout Creek sites, its upstream drainage area, estimated from 30-m DEM, is 31.7 km^2, approximately half that of the entire Lookout Creek watershed and a little more than five times that of the Mack Creek sites (Table 9.1). The average channel gradient is 3.2%, or about one third of the gradient at the Mack Creek sites and less than a fifth of the gradient of the Cold Creek site. The average channel width is approximately 24.7 m, roughly double that of the Mack Creek sites and nearly 5 times that of the Cold Creek site.

Two key characteristics of the LOM site are the absence (mostly) of hillslopes adjacent to the channel and the abundance of large, fluvially transported LWD. Among cross section sites, the LOM site is unique in being mostly unconstrained by surrounding topography (Table 9.1, Figure 9.7). The channel is adjacent to a hillslope only on the left bank of the lower 100 m of the reach. Elsewhere the channel is bordered by extensive floodplain surfaces (mostly less than 1.5 to 2 m above the low-flow channel), covered with old-growth conifer and mixed conifer-hardwood forest. On the left bank, the channel is bordered by a floodplain approximately 1 to 2.5 m (mostly <1.5 m) above the current summer low-flow water surface. This surface is vegetated with old-growth Douglas fir, hemlock, cedar, and bigleaf maple, extending from approximately 75 m upstream of the uppermost cross section down to XS 7, a distance of approximately 260 m. At the upstream end of this surface, a large side channel branches off from the main channel and follows a large arc to the south (presumably a former meander bend of Lookout Creek), returning to the main channel just upstream of the x-post for XS 7 and 8 (Figure 9.6, location E). The entrance of the side channel (not shown in Figure 9.6) is partially blocked by LWD and sediment, and no surface water enters under summer low flow conditions, although some flow in the channel is maintained via subsurface flow. At approximately the southernmost extent of the arc, a small perennial tributary flows into the side channel. The outside

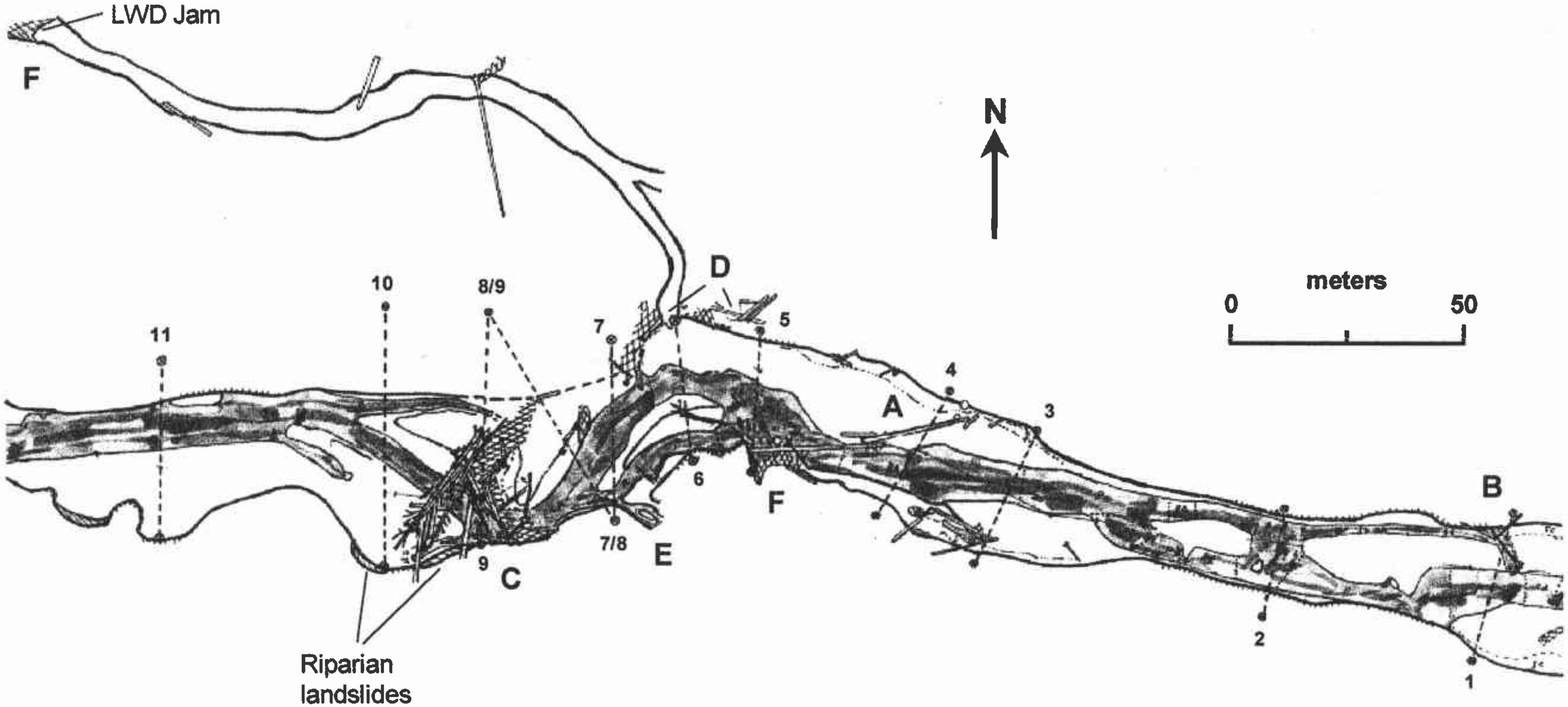


Figure 9.6. Map showing channel features and cross section locations at the middle Lookout Creek (LOM) site, fall 1996. Letters identify locations of features referred to in text: A – large log anchoring up- and downstream bars; B – marginal LWD accumulation anchoring upstream bar and protecting downstream bar; C – channel-spanning LWD jam formed in February 1996 flood; D – entrances to back channels in floodplain, plugged by sediment and woody debris; E – junction of combined back channel and small tributary with main channel; F – marginal LWD accumulation anchored by channel-spanning log; G – LWD jam in back channel emplaced in February 1996 flood.

Figure 9.7. View of stream channel and adjacent forested floodplain at the middle Lookout Creek (LOM) site (near location A in Figure 9.6).

edge of the side channel and the floodplain surface it bounds is marked by a short, abrupt 6 to 10-m high slope that is most likely the edge of a dissected alluvial fan.

Downstream of where the side channel rejoins the main Lookout Creek channel, the left bank of the channel takes on a scalloped appearance and becomes a sheer wall at the foot of a steep hillslope. Since the February 1996 flood, portions of the bank where the current has been forced against the bank by a massive accumulation of LWD and associated sediment (Figure 9.6, location C) have slumped down into the channel carrying several large conifers with them.

On the right (north) bank, bank height decreases fairly abruptly from ≥2 m upstream to <15 m downstream of XS 2. A forested flooplain surface extends approximately 50 to 125 m north of the channel edge, to the edge of Road 1506 in the upstream portion of the reach or the edge of a 2 to 4-m high terrace bordering the downstream end of the reach. A network of back channels, some of which are shown in Figure 9.6, dissect the forested floodplain surface downstream of XS 5; less well-defined channels and evidence of lateral overflow from the main channel extend upstream as far as XS 3. Major back channel entrances, partially plugged by LWD and sediment, are located by cross section posts 5Z and 6Z in the central portion of the LOM reach (Figure 9.6, location D). The main back channel shown in Figure 9.6 is lower than the main Lookout Creek channel, and its entrance by XS 6 is less than one meter above the summer low-flow water surface. This back channel has year-round flow via hyporheic flow from the main channel.

As noted above, the LOM site contains abundant LWD including old-growth conifer logs. Unlike the Cold Creek and Mack Creek sites, most of the LWD within the LOM reach, including large logs, has been fluvially transported, and is concentrated in large marginal or channel-spanning accumulations. Many of the logs have cut ends. A major feature of this reach is a massive accumulation of LWD along the right (north) bank of the channel extending downstream from the vicinity of XS 5 (Figure 9.6, location D) and spanning the channel in the vicinity of XS 9 (Figure 9.6, location C). Much of this LWD predated the February 1996 flood and probably was emplaced by the 1964 flood, but a channel spanning accumulation, which partially blocks the main channel in the vicinity of XS 9, was created by the 1996 flood.

The LOM site is typical of many 4th-order reaches in the western Cascades in that it is downstream of dozens of clearcuts (but is not bordered by any). It is atypical in its geomorphic setting within a wide alluvial valley floor segment caused by deposition upstream of a massive earthflow (Section 9.1; Swanson and James, 1975a). Wide valley floors are more typical of the Washington Cascades, which have been more heavily glaciated. The LOM site is upstream of most documented debris flows (Figure 9.1), and where the valley floor is wide tributary debris flows often stop before reaching Lookout Creek (Grant and Swanson, 1995), so it is probably not strongly affected by mass movement processes. Several known active earthflows occur upstream of the Mack Creek confluence, but are too far upstream to have much direct influence on the channel at the LOM site.

9.1.5 Lower Lookout Creek Site

The lower Lookout Creek (LOL) site consists of 14 cross sections along a 470-m long reach of 5th-order Lookout Creek (Figure 9.8) located approximately 450 m upstream of the Lookout Creek gaging station (Figure 3.1). The upstream drainage area is approximately 61.5 km^2, very nearly double that of the LOM site, while the average channel gradient is slightly less than half that of the LOM site at 1.5% (Table 9.1). With an average channel width of approximately 27.3 m, however, it is only slightly wider than the LOM site (24.7 m), although the lower two-thirds of the reach is slightly wider (29.3 m).

A sharp (>90°) left bend, in which the channel has been pinched against a bedrock wall on the right bank by an alluvial fan (currently inactive) on the left bank, divides the reach into two distinct parts (Figure 9.8, location A). In the upper part (not shown in Figure 9.8), the stream flows to the northwest, bending slightly toward the west before entering the sharp southward bend. The channel runs along the foot of a steep hillslope on the right, while the left bank is bordered by a more gently sloping surface that is probably an inactive alluvial fan. Downstream of the sharp bedrock bend, the channel abruptly widens and the stream flows nearly due south for approximately 230 m. A large, high bar, approximately 130 m long by up to 20 m wide (Figure 9.8, location B), separates the current channel along the east bank from the former main channel (abandoned during the February 1996 flood) along the west bank. Downstream of this bar, the channel narrows and bends approximately 25° toward the west. About 90 m downstream of this second bend, the channel enters a narrow bedrock gorge just below the lowermost cross section (XS 1, Figure 9.8).

Downstream of the bedrock bend, the left (east) bank of the channel is a 4- to 6-m high terrace in which fluvial sediments (presumably older Lookout Creek sediments) unconformably overlie a debris flow deposit, which presumably originated in watershed 2 (WS 2; Figure 3.1), and varved glaciolacustrine sediments (Gottesfeld et al., 1981). Gottesfeld et al. reported a piece of wood from the debris flow deposit to have a carbon 14 date of greater than 35,500 years B.P. The stream appears to be actively eroding the terrace for approximately 200 m from the bedrock bend

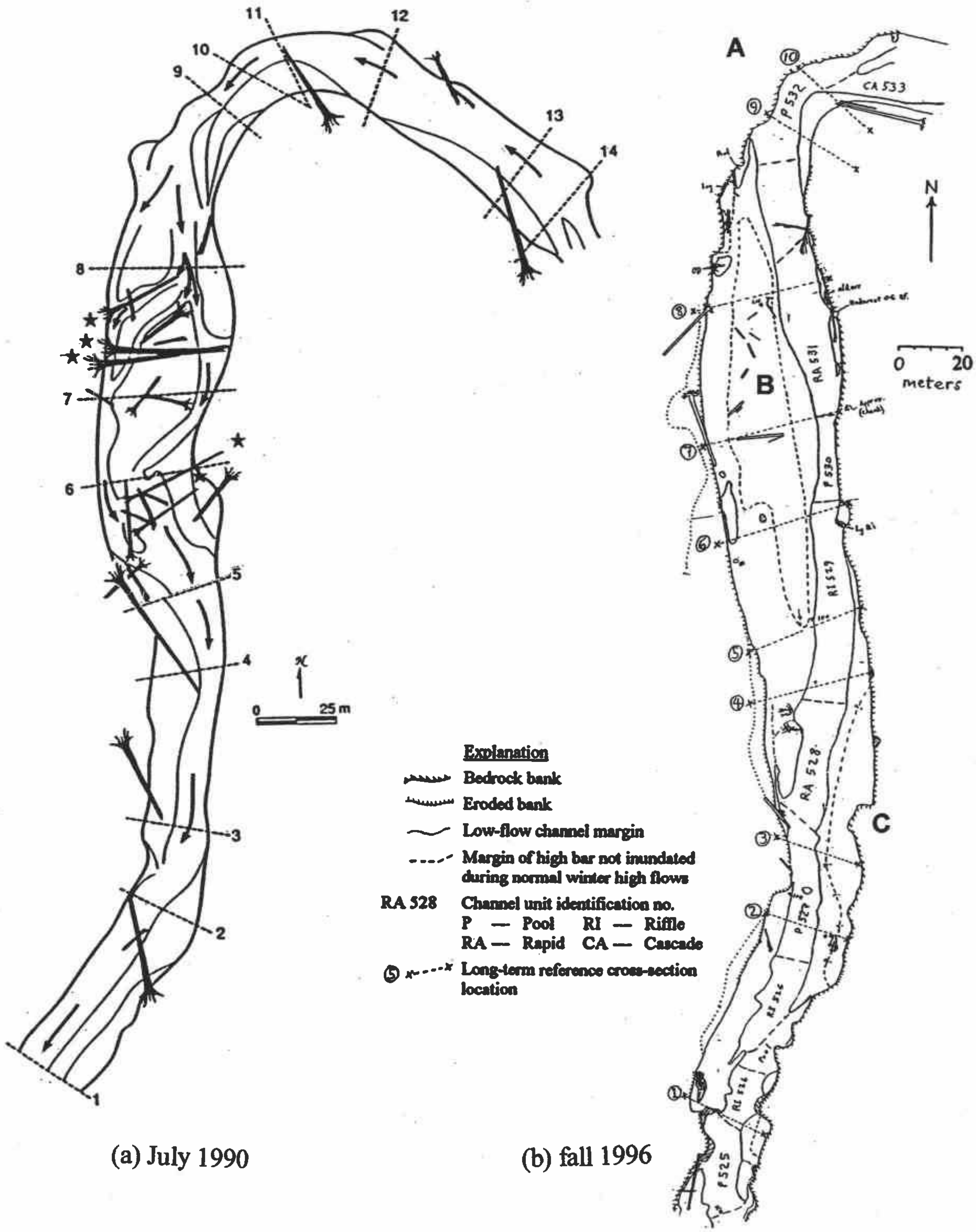


Figure 9.8. Maps of channel features at the lower Lookout Creek (LOL) site: (a) July 1990 (from Nakamura and Swanson [1993]); (b) fall 1996 (by author). Letters identify locations of features referred to in text: A – bedrock-constrained bend; B – large separating abandoned channel (west of bar) from new channel formed by the February 1996 flood; C – bedrock outcrop at constriction and bend in channel.

downstream to a bedrock projection just upstream of XS 3 (Figure 9.8, location C). On the right (west) bank downstream of the bedrock bend, a low terrace or floodplain surface approximately 1.5 to 2.5 m above the low-flow channel extends downstream from the vicinity of XS 8 to XS 1, reaching a maximum width of about 30 m. This surface is covered with old-growth conifer forest and is bordered on the west by a high terrace on which the H.J. Andrews headquarter facilities are located.

Cross sections in the LOL reach are quite irregularly spaced, particularly in the upper part of the reach. In the upper sub-reach above the sharp bend, the two uppermost cross sections (XS 13 and 14) are only approximately 25 m apart, followed by a more than 60-m gap to the next cross section. This is followed by three closely spaced cross sections (XS 9 to 11) within the bend, and then by eight somewhat irregularly spaced cross sections in the next approximately 300 m downstream of the bend (Figure 9.8).

Prior to the flood of February 1996, LWD was fairly abundant within the portion of the LOL reach downstream of the bedrock bend, including a number of old-growth Douglas fir and cedar logs, which spanned the channel or projected from the banks into the channel, but most of this wood was evacuated from the reach during the flood. Changes in LWD and the channel planform over time at the LOL site are discussed in Section 10.2.5.

The LOL site differs from the LOM site in that it is much more highly constrained by adjacent valley walls and valley floor landforms (i.e., alluvial fans and terraces), although the abrupt local widening in channel and valley floor width downstream of the sharp bend at the LOL site may cause the portion of the reach downstream of this feature to behave more like an unconstrained reach. The LOL site is downstream of numerous documented debris flows, many of which have reached Lookout Creek (Figure 9.1). One unique aspect of the LOL site is the clearing for the Andrews Forest headquarters to the northwest, which may conceivably have exacerbated windthrow in this reach, causing LWD input to be higher than it otherwise would be. Overall, the LOL site is probably more representative of "typical" 4th to 5th-order mainstem channels in the western Oregon Cascades than is the LOM reach.

9.2 Field Methods—Historical Data

9.2.1 Cross Section Monitoring

Reference cross sections were first established in 1978 at the lower Lookout Creek (LOL), middle Lookout Creek (LOM) and Mack Creek old-growth (MAC) sites, and in 1980 and 1981, respectively, at the Cold Creek (COC) and Mack Creek clearcut (MCC) sites (Figure 3.1). Between 11 and 20 cross sections were established at each site (Table 9.1). Cross sections were irregularly spaced to sample a range of channel environments (pools, riffles, etc.). Endpoints of each cross section were marked by steel fence posts or in some cases (on bedrock or resistant cohesive banks) by an eyebolt or a steel rebar stake. Cross sections were resurveyed annually between 1978 and 1999 except in years which did not have significant storms (Table 9.2). The longest interval between re-surveys was five years, between 1990 and 1995, a hydrologically quiescent period during which only the 1995 peak discharge approached the mean annual flood in Lookout Creek. Beginning in 1995, black-and-white photographs of each cross section, typically one upstream and one downstream view, were routinely taken during cross section surveys.

Cross sections were surveyed according to a standard protocol using an auto-level (an instrument with an optical self-leveling mechanism that maintains a true level line-of-sight once the instrument is approximately leveled by hand) and a telescoping fiberglass stadia rod graduated in 0.5-cm increments, as described in Section 3.2. However, the equipment and protocol used in surveying the cross sections changed somewhat over time, a fact which should be taken into account when interpreting the data. Up until the mid-1980s, the cross sections were surveyed using a Dumpy level, an instrument which can be used for either level or inclined sightings. This instrument required careful attention to maintaining a level line of sight to achieve accurate results. Inclined sightings (in which the angle between the telescope line-of-sight and the horizontal plane was recorded and a trigonometric correction applied to the elevation data) were occasionally used during this period when vertical relief within the cross section exceeded the height of the stadia rod. An auto-level was

Table 9.2. Summary of cross section data availability.

Water Year	Max. Q_{pk} (m^3/s)(1)	Site LOL	LOM	MCC	MAC	COC
1978	**86.4**	Yes	Yes		Yes	
1979	32.8					
1980	44.2	Yes	partial		Yes	Yes
1981	**62.9**	Yes	Yes	Yes	Yes	Yes
1982	49.6	Yes	Yes	Yes	Yes	Yes
1983	41.6			partial	Yes	
1984	**59.5**	Yes	Yes	Yes	Yes	Yes
1985	32.0	Yes	Yes	Yes	Yes	Yes
1986	**76.5**	Yes	Yes	Yes	Yes	Yes
1987	27.5					
1988	30.9	Yes	Yes	Yes	Yes	
1989	47.6	Yes	Yes			
1990	55.5	Yes	Yes	Yes	Yes	
1991	28.6					
1992	31.4					
1993	34.5					
1994	23.4					
1995	50.1	Yes	Yes	Yes	Yes	Yes
1996	**226.5**	Yes	Yes	Yes	Yes	Yes
1997	**84.4**	Yes	Yes	Yes	Yes	Yes
1998	41.6	Yes	Yes			
1999	55.8	Yes	Yes			
Avg.(2)	56.1					

Notes

Yes = cross sections surveyed in indicated year

partial = subset of cross sections surveyed in indicated year

(1) Maximum instantaneous discharge during year at Lookout Creek gage. Values in **boldface** exceed mean annual Q_{pk}.

(2) Mean annual instantaneous peak discharge for 1950-98.

first used for surveying the cross sections in either 1986 or 1988. In an effort to improve data consistency, the cross section survey protocol was modified and standardized in 1986 (Henshaw, 1986). Prior to to this time, elevations were measured at irregular intervals along the line of section at slope breaks and other points selected to capture important topographic and geomorphic features and changes in substrate type. The frequency of surveyed points along each cross section varied considerably from year to year, resulting in a variable degree of resolution in characterizing the channel cross-sections. The categories used to classify the substrate material also varied from year to year until 1982, when substrate codes were standardized and data from previous surveys were reclassified to conform to the new scheme.

In addition to standardizing the sampling interval, several additional steps were taken to improve data quality in 1986. Cross section end posts were better anchored (where necessary) and labeled; attachment points on each cross section end post were identified and marked to ensure that the tape would be at least approximately level (so that horizontal distance measurements would be accurate and consistent between survey dates); and a check of the cross section length was made prior to surveying to ensure that it was consistent with previously measured values. Previously, no effort was made to ensure that the tape was approximately level (or to correct the horizontal distance for the effects of an inclined tape) or that the measured section length matched previous survey data. At several cross section locations at the lower Lookout Creek site, where one end post was located on a high terrace, intermediate posts were established lower on the bank in 1986 at an elevation closer to that of the post on the opposite bank; the intermediate posts subsequently served as the new cross section end points.

Beginning with the 1995 survey, modified Wolman (1954) pebble counts were performed in conjunction with the cross section surveys to characterize bed material surface particle size and its spatial and temporal variability. Pebble counts were performed at each cross section location at the Lookout and Mack Creek sites and within 3 sub-reaches at the Cold Creek site, where the small channel size makes individual cross-section based counts impractical. Pebble counts consisted of measuring the intermediate-axis diameter of 100 particles selected at random from the streambed within the active channel floodway and within approximately one to two meters up- and downstream of the cross section line. Particles were selected by traversing the channel along the cross section line and reaching down with one finger while looking away from the streambed to avoid biasing selection. Each particle was measured to the nearest 5 mm (or the nearest 1 mm for particles less than about 5 cm in diameter) using a steel tape measure. Particles less than 2 mm in diameter (i.e., sand) were recorded simply as <2 mm. For large partially buried particles, the length of the apparent intermediate axis of the exposed portion of the particle was measured.

9.2.2 Streamflow Monitoring

The U.S. Geological Survey (USGS) has operated a stream gage near the outlet of the Lookout Creek basin since 1950, and several tributaries have been gaged by the U.S. Forest Service (USFS) using flumes installed between 1952 and 1980 as part of a series of paired watershed experiments, in which the hydrologic response of small watersheds manipulated by various treatments (e.g., partial or total clearcutting) was compared with that of control (unaltered) watersheds (Jones and Grant, 1996). Discharge data from the Lookout Creek gage and the control watershed gages operated by the USFS were used in this study. The locations of the gages are shown in Figure 3.1, and characteristics of the gaged watersheds are summarized in Table 9.3. Data were obtained from the H.J. Andrews Long-Term Ecological Research (LTER) Site online database (http://www.fsl.orst.edu/lter/ datafr.htm) and from the USGS National Water Information System database (http://waterdata.usgs.gov/nwis-w/US/).

9.3 Field Methods—Supplemental Data

Additional field data were collected between the fall of 1996 and the fall of 1998 to more completely characterize channel morphology within the study reaches. Field work performed at each study reach included (1) a survey of the cross section

Table 9.3. Characteristics of gaged watersheds used in this study.

Characteristic	Lookout	Mack	WS 2	WS 8	WS 9
Drainage area, km^2	62.4	5.8	0.60	0.21	0.09
Elevation at gage, m	428	758	548	993	432
Max. elevation in watershed, m	1620	1610	1070	1170	700
Year established	1950	1980	1953	1964	1969
Years of record (through 1998)	49	19	46	34*	29*
Max. historical peak discharge, m^3/s	227#	9.35	1.30	0.41	0.13
Mean annual peak discharge, m^3/s	56.1	5.16	0.47	0.16	0.07
Min. annual peak discharge, m^3/s	8.30	2.37	0.09	0.04	0.02
Max. peak unit area discharge, $m^3/s/km^2$	3.63#	1.61	2.16	1.90	1.56
Mean peak ann. unit area discharge, $m^3/s/km^2$	0.90	0.89	0.77	0.74	0.86
Min. peak ann. unit area discharge, $m^3/s/km^2$	0.13	0.41	0.16	0.19	0.25

* 1998 data not available for WS 8 and WS 9
# estimated value

endpoint stakes; (2) mapping the channel including the margins of the low flow channel and active channel floodway, channel unit types, the positions of large logs and woody debris accumulations, and other salient channel features; and (3) surveying a high-resolution longitudinal profile of the channel thalweg.

9.3.1 Cross Section Endpoint Surveys

End post locations for each cross section were surveyed during the summer of 1997 to accurately establish the spatial relationship of the cross sections to one another. The relative elevations and map locations of the cross section reference posts (measured at the ground surface) were surveyed using a builders' auto-level and laser theodolite as described in Section 3.3.1.

9.3.2 Mapping of Study Reaches

Each study reach was mapped by tape-and-compass (lower and middle Lookout Creek, Figures 9.8 and 9.5, respectively), laser theodolite (Cold Creek, Figure 9.3), or a combination of the two methods (Mack Creek, Figure 9.4). In tape-and-compass surveys, a fiberglass surveying tape was stretched tautly between temporary steel rebar survey stakes driven into the streambed (or, in some cases, into large logs in the channel). The bearing of the baseline tape was then carefully measured using a staff compass graduated in ½-degree increments. Locations of fixed reference points (e.g., cross section end posts) were determined by measuring the distance between the point of interest and two or more points on the tape using a second fiberglass tape, noting which side of the baseline (left or right relative to a downstream-facing observer) the feature was on to obtain a unique plotting location. Other points of interest (points along the channel margins, endpoints of logs within the channel, etc.) were surveyed by measuring the perpendicular distance from a known point on the baseline and recording the baseline tape distance, perpendicular distance, and direction (left or right of the tape, facing downstream). All measurements were recorded to the nearest 0.1 m. A handheld compass was used to ensure that the measurements were made perpendicular to the baseline tape. Points along the edge of the wetted channel at the time of mapping (low-flow channel) and the margin of the active channel floodway were surveyed at intervals sufficient to define the channel margins (typically ¼ to ½ channel width or less).

The surveyed points were plotted by hand on water-resistant paper in the field or office at a scale of 1:1000 or greater. The channel margins were then sketched in in the field, and details such as large boulders or logs, bedrock outcrops, and scoured or undercut banks were added to the map.

For the Mack Creek and Cold Creek sites, a laser theodolite was used to survey the locations of points along the active channel floodway margins in a manner similar to that described below for the longitudinal profile surveys. These points were marked in the field by flagging tape or survey flags bearing unique ID numbers noted on the survey data form. After the map coordinates of these points relative to an arbitrary starting point (one of the cross section posts) had been calculated and plotted by computer, the plot was taken into the field and the details of the channel margins were sketched in by hand. Further details (logs, large boulders, channel unit boundaries) were then added by tape-and-compass survey using the channel margin flags as reference points.

9.3.3 Longitudinal Channel Profile Surveys

Cross-sections at best offer only an incomplete characterization of channel morphology in high-gradient streams such as those within the Lookout Creek watershed, which tend to develop a stepped structure in longitudinal profile (Grant et al., 1990). Therefore, a high-resolution longitudinal profile was surveyed along the channel thalweg for the entire length of each of the study reaches to supplement the cross sections. At Mack Creek, a longitudinal profile of approximately 1 km of the channel, including both the old-growth and clear-cut sites, was surveyed (Figure 4.1).

The survey was performed using the laser survey instrument described in Section 3.3.1. One member of the 2-person survey crew operated the instrument and recorded all data, while the other selected points to be surveyed and held the staff bearing the reflecting target vertically at the point to be surveyed. The person on the staff also estimated the water depth to the nearest centimeter at each location using 5-cm gradations on the reflector staff, and noted the substrate type. For each point occupied, the following data were recorded: horizontal distance, vertical distance, compass bearing, staff height (to center of reflecting target), water depth, and substrate code(s).

Substrate categories were the same as those used for the cross-section surveys. However, rather than recording the substrate immediately beneath the reflector staff, the dominant substrate within a 25-cm radius around the staff was recorded. If two substrate types each comprised greater than 1/3 of the area within a 25-cm radius, based on a visual estimate, a primary and secondary substrate type were recorded. To maintain data consistency, field crew members kept the same roles throughout the duration of the project.

At the Mack and Cold Creek sites, points were selected along the main channel thalweg at intervals of approximately one meter, or a smaller interval where necessary to characterize abrupt changes in channel slope or elevation—e.g., at the crest and base of abrupt steps in the longitudinal profile. At the Lookout Creek sites, a slightly longer interval—up to 1.5 m—was used. At points where the flow divided around a mid-channel bar, the profile followed the larger channel (or in some cases both channels). The location of any steps greater than about 30 cm in height was noted in the comment column of the field notes. When traversing pools, it was attempted to include the upstream and downstream endpoints of the pool as well as the deepest point located along the thalweg.

Survey data were entered into a spreadsheet, where the measured compass bearings and horizontal and vertical distances were used to calculate the coordinates (x,y,z) of each point with respect to an arbitrary reference point (one of the previously surveyed cross section end posts).

9.4 Corrections and Adjustments to Cross Section Survey Data

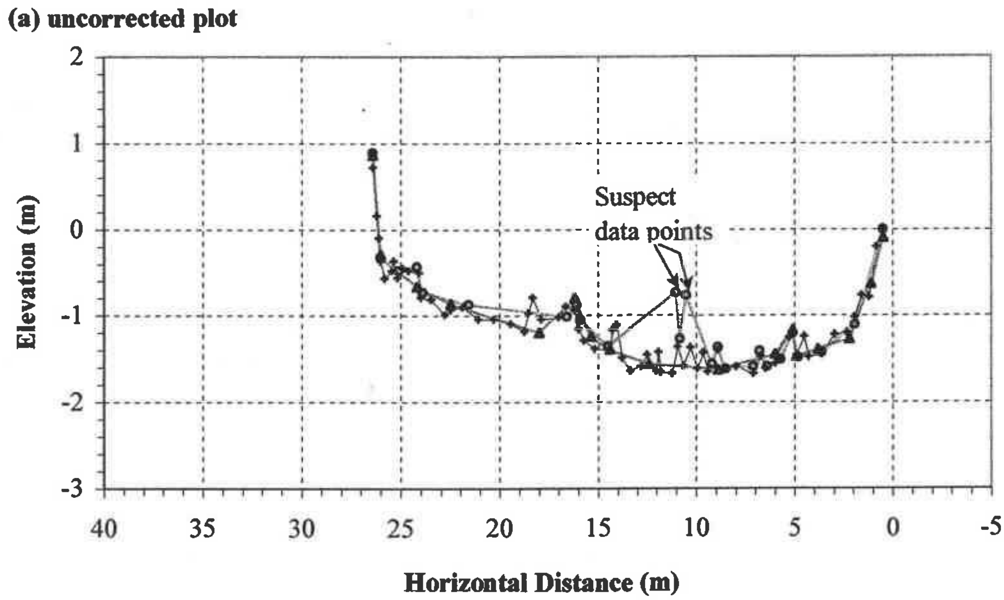
The historical cross section data contain a number of sources of potential measurement error or uncertainty in comparing between successive cross section surveys. A systematic process of data verification (i.e., error detection and correction; Section 9.4.1), adjustment of cross section profile alignment (Section 9.4.2), and filtering to remove errors associated with LWD (Section 9.4.3) was implemented to minimize these potential errors and maximize the amount of useful information that could be extracted from the cross section profiles. In addition, the data were scaled (Section 9.4.4) to allow between-site comparisons of channels of larger and smaller channels. Resulting *un*scaled cross section plots after error correction, alignment, and filtering are included in Appendix B.

Cross section survey data for 1996 and prior years were obtained by the author from the H.J. Andrews LTER database (http://www.fsl.orst.edu/lter/datafr.htm) and converted from units of centimeters to meters prior to processing. Data from 1997 and subsequent years were entered and proofed from the original field notes by the author prior to the steps described below.

9.4.1 Sources of Error and Uncertainty

Surveying errors can affect either the horizontal coordinate, the vertical coordinate, or both for individual data points in cross section profiles. Measurement errors affecting the vertical or z-coordinate can result from incorrectly reading the level at which the telescope crosshair intersects the stadia rod. Surveying errors that can affect the horizontal or x-coordinate can result from incorrectly reading the position of the rod on the tape, which is particularly a problem when the cross section tape is high above the channel bed. Failure to hold the stadia rod vertically or incorrectly or illegibly recording the data can result in both horizontal and vertical errors.

Perhaps the most common—or at least the most readily detectable—error was recording the wrong value for the first digit (i.e., the meter mark) of the crosshair reading, due to the fact that often no meter mark is within the field of view of the level telescope and only the decimeter and centimeter markings can be seen, particularly on short distance shots where the field of view is small. The likelihood of misreading the meter value is highest when transitioning from one meter interval to the next higher or lower interval—for example, if a series of points with crosshair values in the range of 1.8 to 1.9 m are followed by a point at, say, 2.17 m, the value might be misread (or mis-recorded) as 1.17 m if the change in the first digit is missed. Fortunately, this error is often readily apparent when inspecting the cross section profile plots (Figure 9.9[a]), particularly if only one or two points are affected and the profile did not otherwise exhibit large changes from the previous survey, because abrupt spikes or troughs with a 1-m amplitude are rare within channels and are typically attributable to logs or large boulders (which tend to remain in the same place for a long time). Where such spikes or troughs were present during one survey but were absent in preceding and subsequent surveys, the z-coordinate was corrected by ± 1 m on the



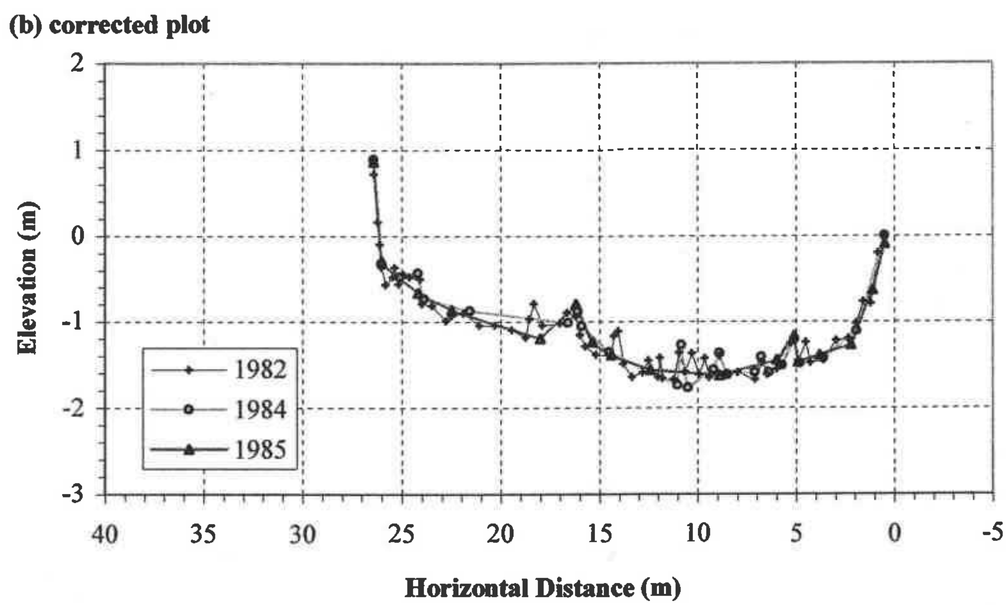


Figure 9.9. Correcting inferred surveying errors from inspection of cross section profile plots. (a) Uncorrected plot; two suspect data points create large apparent change between the 1984 profile and both the 1982 and 1985 profiles. Apparent change is magnified by sparsity of data points in the 1984 and 1985 surveys. (b) Corrected plot. The elevations of the two suspect points have been adjusted by -1.00 m to correct the inferred surveying error. The corrected plot shows little apparent change between the 1984 and 1985 profiles; small apparent differences between the 1982 profile and the later profiles are mainly due to the higher resolution of the 1982 survey.

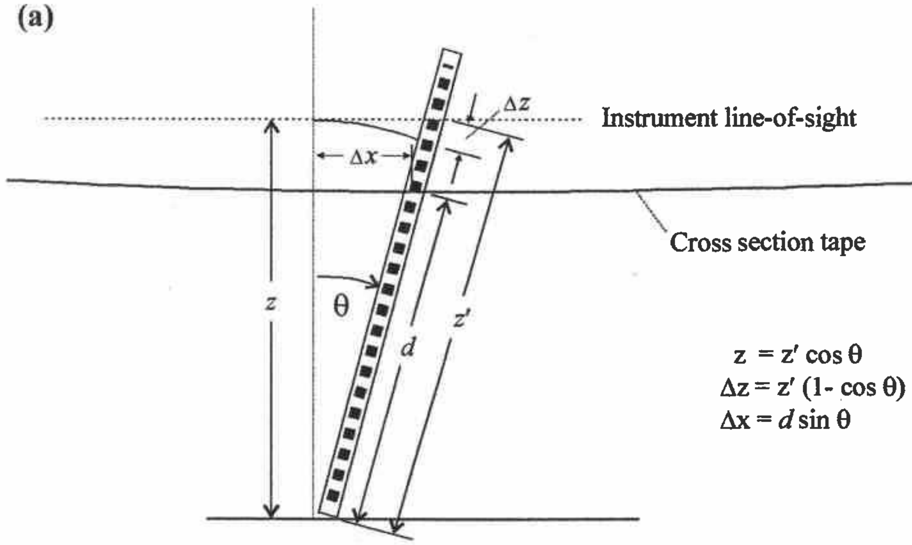
assumption that an error had been made in reading or recording the first digit of the crosshair intercept (Figure 9.9[b]).

Other surveying errors are more difficult to detect and correct. Errors in the second or third digit of the crosshair intercept cannot be detected by inspection of cross section profiles; however, errors of 0.1 m or less are relatively insignificant and would not affect interpretation of the profile data. Errors in the horizontal or x-coordinate have little effect where the streambed is flat or gently sloping along the line of the cross section, but can significantly affect the apparent position of steeply sloping surfaces such as the stream bank or the edge of a bar.

Failure to hold the stadia rod vertically during surveying can result in errors in both the vertical and horizontal coordinates (Figure 9.10[a]). The vertical error from this source is generally insignificant; for example, if the rod is 5° out of vertical (an amount readily perceptible to an observer) and the apparent crosshair intercept is 2.00 m, then the true vertical height of the crosshair intercept above the base of the rod is $2.00 \times \cos 5°$ or 1.99 m. However, if the rod leans in a direction parallel to the tape and the tape crosses the rod at a height of 2 m, then the difference in the position of the base of the rod (vertically beneath the tape) and the position of the rod where it crosses the tape would be $2.00 \times \sin 5°$ or 0.17 m. If the rod crossed the tape at a height of 5 m (not uncommon in early surveys of some profiles at the lower Lookout Creek site), the error in the x-coordinate would be 0.44 m. Exacerbating this problem is the fact that the telescoping stadia rods used in surveying the cross sections bends at the joints between segments (Figure 9.10[b]), making it often difficult or impossible to hold the rod truly vertical when it is extended beyond the first 2 segments (about 3 m).

The factors discussed above affect the accuracy of the x- and/or z-coordinates of individual points within a cross section profile. Other sources of error affect the entire profile. By far the most important consideration in this regard is the lack of a true fixed reference point for each profile. Although the profile endpoints were monumented in the field by relatively permanent posts or stakes, these markers do not define a precise point in three-dimensional space (Figure 9.11). In essence, each section has two possible reference points—the ground surface at the base of each end post or stake. However, since the ground surface or bank in which the end posts or

(a)



(b)

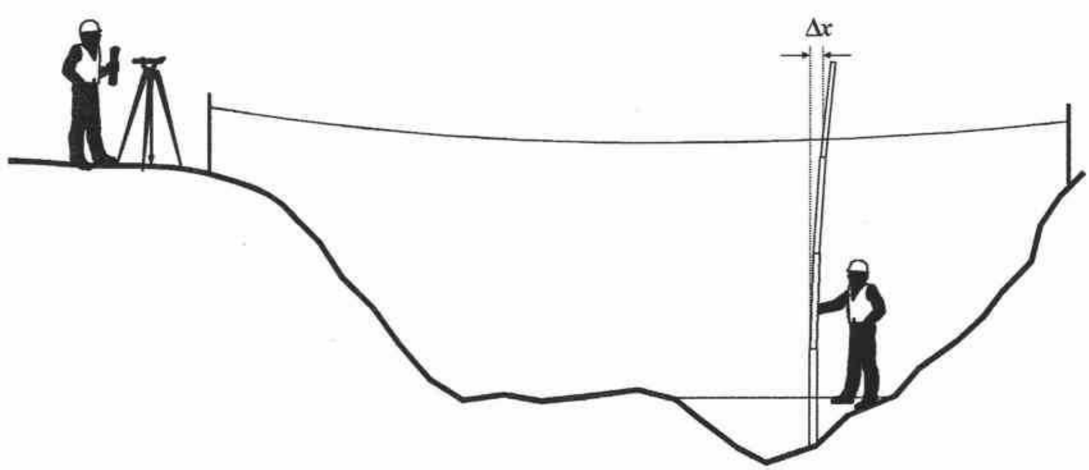


Figure 9.10. Effects of stadia rod lean on cross section survey errors: (a) errors in vertical (z) and horizontal (x) coordinates resulting from non-verticality of a straight rod; (b) error in measuring the horizontal position of a segmented stadia rod due to hinging at segment joints.

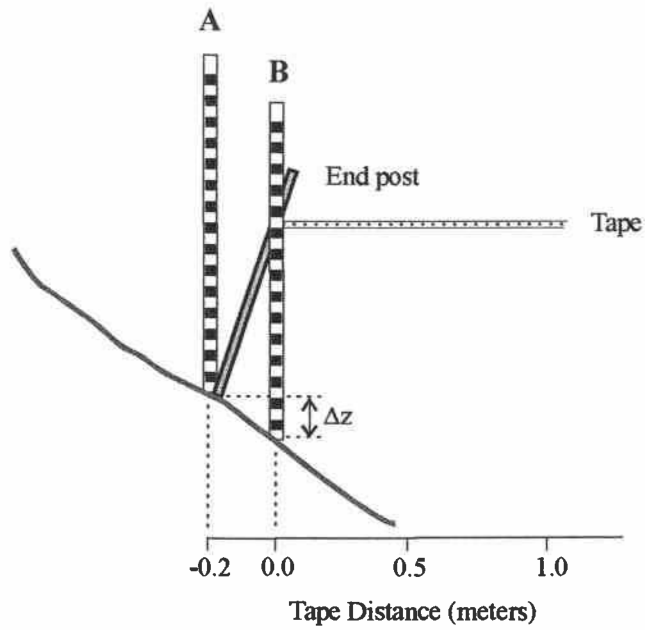


Figure 9.11. Effects of cross section end post lean and stadia rod placement on location of cross section endpoint. Positions labeled A and B identify two possible interpretations of the cross section starting point.

stakes are emplaced is typically sloping (in some cases vertical!) and often spongy and/or uneven, and since the end posts are physical objects rather than dimensionless geometric points, the "base of the post" does not precisely specify a unique point in space. Hence, it matters on which side of the post—upstream, downstream, inboard (toward the channel) or outboard (away from the channel)—the stadia rod is placed when surveying the profile endpoints. Unfortunately, no firm criteria for where the stadia rod should be placed when surveying the profile endpoints were ever established.

Other factors, such as post lean, complicate the matter of defining where exactly the endpoint of the cross section lies. In Figure 9.11, the post leans inward (toward the channel), which is a common occurrence (probably due to a combination of soil creep and the tension applied when the tape is stretched between the two posts). The obvious (and most appropriate) place to put the stadia rod in this case is at the base of the post on the inboard side, in which case the correct horizontal distance (x-coordinate) to use would be the value at the point where the tape crosses the rod at position A, not the value at the point where the tape attaches to the post (i.e., -0.2 m, not 0.0 m). Alternatively, the stadia rod might be placed next to the post at the point of attachment of the cross section tape (position B in Figure 9.11), in which case the correct horizontal distance would be the value where the tape attaches to the post (i.e., 0.0 m in this example). Position A is a better choice than position B, because its location does not change if the tape attachment point or the angle at which the post leans (which depends in part on how much tension is put on the tape) change. However, the tape distance for sightings at the z-post seldom reported as anything other than zero in the historical data, suggesting that either the rod was typically at the tape attachment point (position B in Figure 9.11), or that the tape reading at the attachment point (position B) was used even though the rod was placed at the base of the post (position A). Most likely, in the absence of a clear protocol, different workers probably made different choices over the years.

Failure to correctly level the surveying instrument can also result in systematic errors that affect the z-coordinate values for the entire profile. This is mainly an issue for surveys done prior to 1986, before a self-leveling survey instrument was used (see Section 9.2.1). Correction for this type of error is discussed in the following section.

9.4.2 Adjustments to Cross Section Profile Alignment

A series of adjustments were applied to the cross section profiles to correct for horizontal and/or vertical misalignment of successive profiles surveyed at the same location resulting from the causes described above. As a starting point, profiles from consecutive cross section surveys at a given location were aligned by assuming that the zero-point in the horizontal or x direction, defined as the ground surface at the base of the z-post or stake (the post on the right bank, facing downstream), was always the same point in space and assigning it a local elevation or z coordinate of zero. In cases where this did not result in a good alignment between successive cross section profiles (for example, if the ground surface at the z-post was highly irregular, or if the post was washed out and had to be replaced between surveys) the profiles were aligned at the x-post (on the left bank facing downstream), assuming that *this* represented the same physical point in space. Due to the inexact nature of the reference points and the sources of uncertainty outlined above, however, it was often necessary to further adjust the data to properly align consecutive cross section profiles.

Therefore, four types of corrections were applied to the cross-section data (Figure 9.12), with the default values being zero for additive corrections (cases 2, 3, and 4) and one for multiplicative corrections (case 1):

1. length adjustment, L_{adj}: a multiplicative adjustment of the x coordinate to stretch the profile (values greater than 1) or shrink it (values less than 1) (Figure 9.12[a]). This correction is used to match cross section lengths between consecutive surveys having different reported total lengths for which no real change in length was believed to occur.
2. horizontal offset, x_{adj}: a constant added to the x coordinate of each point to shift the profile to the right (if positive) or left (if negative) (Figure 9.12[b]).
3. vertical offset, z_{adj}: a constant (positive or negative) added to the z coordinate of each point on the cross section to shift the profile up or down (Figure 9.12[c]).
4. tilt adjustment, $\Delta z_{max}/L$: a point-wise, linearly increasing positive or negative additive adjustment to the z coordinate to correct for angular misalignment of cross section profiles attributed an out-of-level instrument line-of-sight (Figure 9.12[d]). This correction was only applied to data from surveys prior to 1986.

For each cross section location, profiles from successive survey dates were aligned by interactively plotting the data and adjusting the above correction factors as necessary, within certain limitations. For each site, the entire time series of cross section surveys was divided into sequences of three or four consecutive survey dates, with the first date of the second and subsequent groupings repeating the last date of the preceding grouping (e.g., 1978, 1980, 1981; 1981, 1982, 1984, 1985; etc.). Profiles for each cross section were then plotted in a series of graphs, one for each time period, allowing the profile for each survey date to be directly compared to the profiles for the next prior and subsequent survey dates. Where profiles for consecutive survey dates

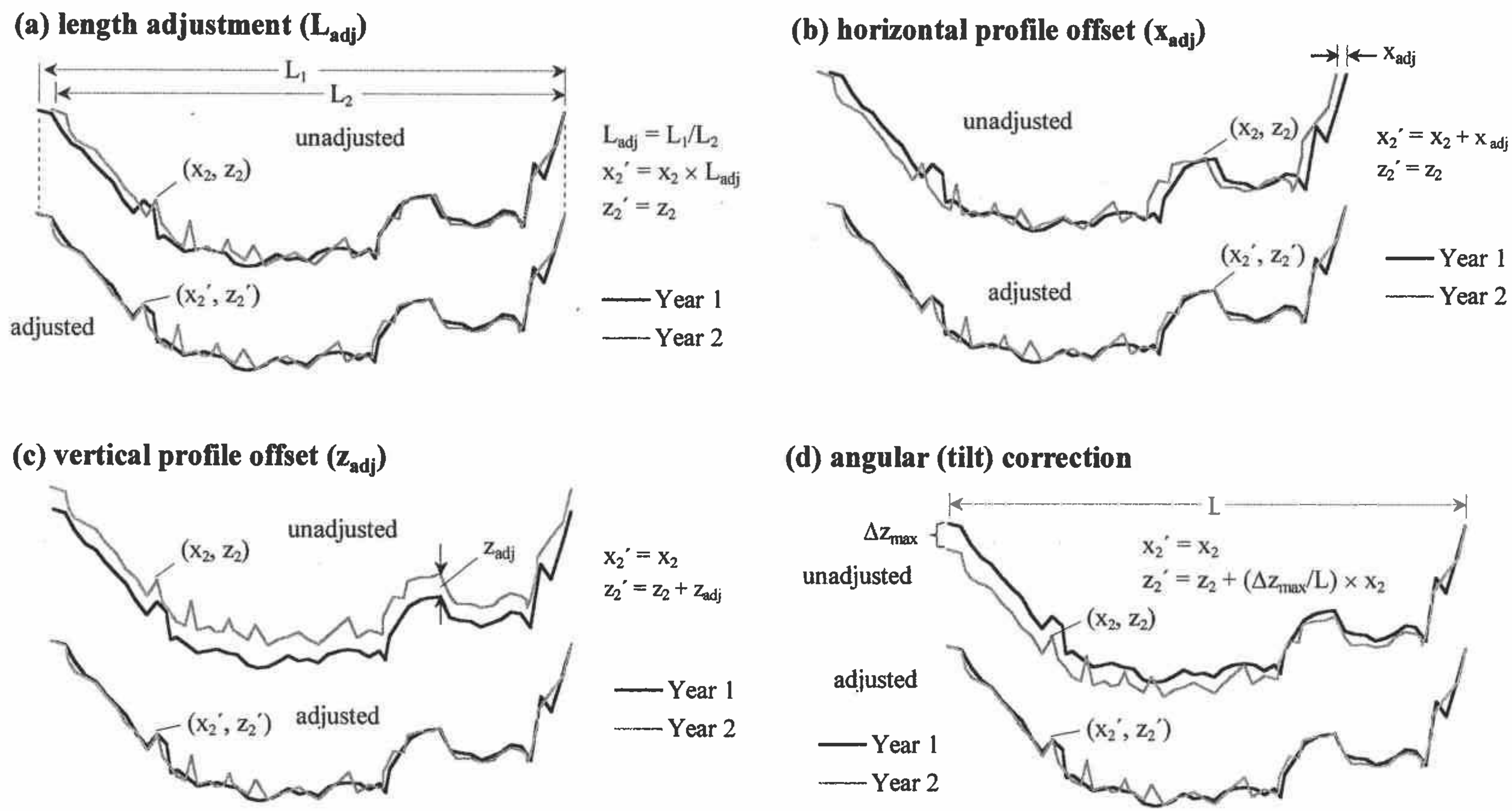


Figure 9.12. Adjustments applied to cross section profiles to align profiles surveyed in different years at the same location: (a) length adjustment, L_{adj}; (b) horizontal profile offset, x_{adj}; (c) vertical profile offset, z_{adj}; (d) angular (tilt) correction. In all examples, the profile for Year 2 is being adjusted to align properly with the profile for Year 1. (x_2, z_2) are the horizontal and vertical coordinates, respectively, for a point on the Year 2 profile, while (x_2', z_2') are the coordinates for a point on the adjusted profile.

appeared to be misaligned, the appropriate correction factor(s) was (were) adjusted until a satisfactory alignment of portions of the cross section profile which did not exhibit change (stable portions of the channel bank, floodplain surfaces, large boulders or logs, etc.) was achieved. The adjusted cross section profiles are presented in Appendix B.

The length adjustment (Figure 9.12[a]), where necessary, was the first correction applied. The reported total length for a particular cross-section commonly varied by 0.1 to 0.2 m (and occasionally significantly more than this) between consecutive survey dates, even though neither endpoint had been relocated, for reasons discussed in the previous section. These minor discrepancies in profile length typically had a negligible effect on between-year profile comparisons and hence were ignored; the length adjustment was only applied where it noticeably improved the match between portions of the cross section inferred to be stable between surveys.

The lateral adjustment, x_{adj}, was applied in two types of cases: (1) when profiles were aligned at the x-post rather than the z-post and the reported tape distance at the x-post was different for the profiles in question, and (2) whenever there appeared to be a constant lateral offset between features with well-defined x-coordinates (such as a near-vertical bank or the top of a boulder), as in Figure 9.12(b).

The most commonly applied adjustment was the vertical constant, z_{adj} (Figure 9.12[c]), which was used to vertically align the cross section profiles. This was often necessary due to the imprecise nature of the elevation control provided by the fixed cross section endpoints, as discussed in the previous section. Stable features having well-defined elevation were used for this purpose, including floodplain surfaces, tops of bars or banks, or the tops of large boulders or logs.

The tilt adjustment was applied in cases where the cross section profile plots suggested that the survey instrument line-of-sight was out of level (Figure 9.12[d]). This correction was applied sparingly, and only on profiles surveyed before 1986, the earliest year in which the auto-level may have been used. Surveys conducted prior to this time were conducted with a manually leveled survey instrument (a Dumpy level), and the practice was to set the instrument up directly over or adjacent to one of the profile end points and sight directly along the line of the cross section. Thus, it is possible to correct for effects of an out-of-level line-of-sight, assuming a constant angular error, as this correction factor does.

9.4.3 Data Filtering to Remove Errors Due to LWD

It is important to filter out logs and woody debris in the cross section profile plots before comparing successive profile plots to infer changes in the channel configuration. Some cross sections cross logs or accumulations of woody debris which are lying on or suspended above the channel bed or banks. Points along the cross section line that are underlain by woody debris (where the stadia rod rests on woody debris during surveying) are not representative of the channel boundary (i.e., the bed or bank). Cross section plots which include such points (especially logs or woody debris which are suspended above the channel) often take on a "spiky" appearance (Figure 9.13[a]) which does not accurately represent the true cross-sectional shape of the channel. In addition, if such points are included in cross section plots, then shifting, rolling, pivoting or other movement of logs or woody debris can result in apparent changes in the channel cross section between consecutive surveys, which may not be representative of actual changes in the configuration of the channel bed or banks.

The substrate code recorded for each data point during cross section surveys was used to identify points to be filtered out of the cross-section profile plot. Points with a substrate code of LG (log), RW (rootwad), RT (root), LS (suspended log), OD (organic debris), or OS (suspended organic debris) were generally excluded from the profile plots if they produced upward spikes (see Figures 9.13 [a] and [b]), but were left in otherwise (i.e., logs or woody debris embedded within and forming part of the channel bed or banks were not excluded from the plots). Points excluded from the profile plots were plotted separately as unconnected points to indicate the presence of logs and woody debris (Figure 9.13[b]).

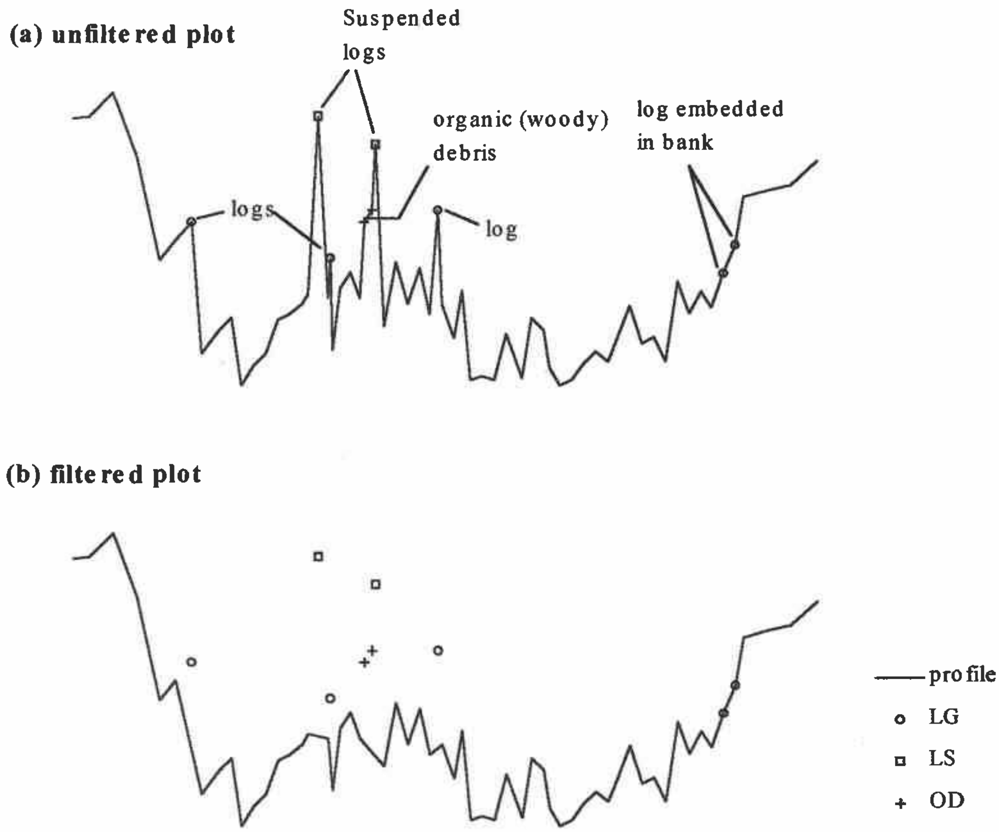


Figure 9.13. Example of the effect of filtering out logs and woody debris on the apparent shape of a cross section profile: (a) unfiltered profile; (b) profile after filtering.

9.4.4 SCALING OF CROSS SECTION PROFILES

Two types of scaling corrections were applied to cross section profiles prior to data analysis to adjust for (1) non-perpendicular alignment of cross sections relative to the channel and (2) different widths of cross sections. First, all cross sections that were not perpendicular to the active channel floodway were orthogonalized by multiplying the x-coordinate of each point by the cosine of the angle, α, between the cross section line and a line perpendicular to the channel (Figure 9.14). For a straight channel of uniform width, a diagonal cross section has a greater apparent channel width and cross-sectional area than a perpendicular cross section (Figure 9.14). To rectify this, α was estimated graphically using the channel map for each study reach, by drawing a line perpendicular to margins of the active channel floodway that

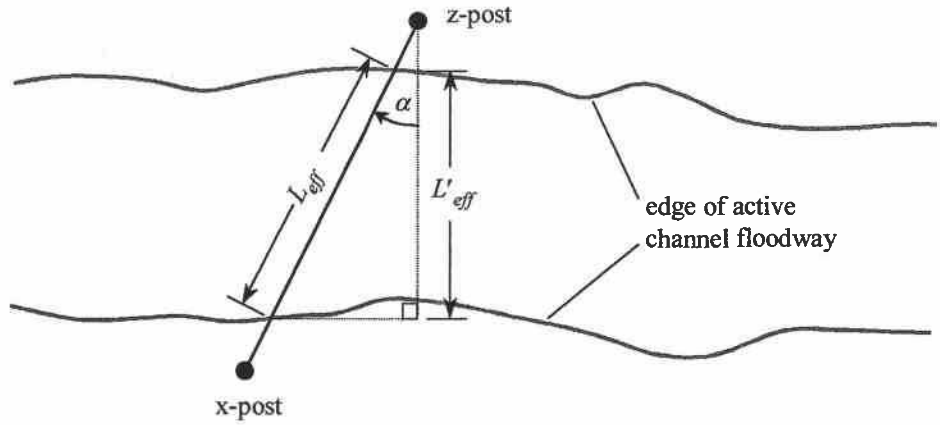


Figure 9.14. Relationship between apparent channel width (L_{eff}) along non-orthogonal cross section and channel width measured orthogonal to the channel (L'_{eff}).

intersects the cross section profile at approximately its midpoint and measuring the angle between that line and the cross section line on the map. This correction had the effect of shortening diagonally elongated cross sections.

The orientation of the cross section relative to the active channel floodway is of interest for purposes of estimating the magnitude of channel adjustment (i.e., erosion and deposition) or performing hydraulic calculations, since channel changes occur during peak flow events when the entire active channel floodway is occupied and the mean flow direction is determined by the active channel floodway margins rather than the low-flow channel margins. The low-flow channel typically only occupies a portion of the active channel floodway, and often meanders within the active channel floodway margins (Figure 9.15). The orientation of the low-flow channel is therefore often different from the orientation of the active channel floodway, and tends to change more readily. Therefore, cross sections may have had four different arrangements relative to the low-flow channel and the active channel floodway: (1) perpendicular to the low-flow channel (and, hence, perpendicular to flow at the time of the cross section survey) but not to the active channel floodway as a whole (e.g., cross section A-A' at Time 1), (2) perpendicular to both the active channel floodway and the low-flow channel (e.g., cross section C-C' at Time 1),

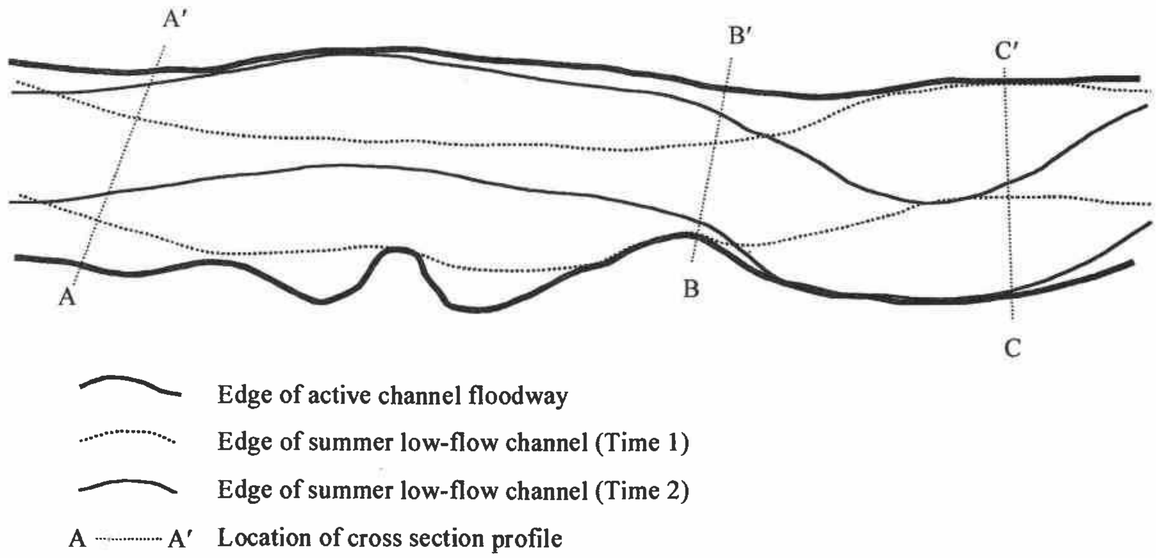


Figure 9.15. Examples of different possible relationships between the orientations of the low-flow channel, active channel floodway, and cross section profiles. See text for discussion.

(3) perpendicular to the active channel floodway but not the low-flow channel (e.g., cross sections B-B' at both times and C-C' at Time 2), or (4) not perpendicular to either the low-flow or active channel floodways (e.g., cross section A-A' at Time 2). For the purposes of this study, it was assumed that the orientation of cross sections relative to the active channel floodway remained constant throughout the monitoring period.

The second scaling adjustment was undertaken to compare among cross sections of different widths. Cross section plots were scaled by active channel floodway width by dividing the x-coordinate values by L'_{eff} (Figure 9.14). This scaling had the effect of converting all x-coordinate values from meters to a fraction of the channel floodway width. This allowed visual classification of cross section responses (described in Section 9.7.1) that could be compared between sites (i.e., between channels of different sizes). The vertical dimension was not scaled. Scaling the vertical dimension would require estimation of the bankfull stage, which is a highly subjective exercise in steep channels such as those at the Mack Creek and Cold Creek sites.

9.5 Other Data Preparation

All cross sections at each site were tied together in 3-dimensional space using the end point surveys, longitudinal profiles and maps (Figures 9.3, 9.5, 9.6, and 9.8). Survey data (see Section 9.3) were entered into an Excel spreadsheet for processing, where the measured horizontal and vertical distances and compass bearings were used to calculate x, y, and z coordinates relative to an arbitrary reference point using standard trigonometric relationships. The axes were aligned with the cardinal directions such that the +x direction is to the east, +y is to the north, and +z is vertically upward.

Particle size data from pebble counts conducted in conjunction with cross section surveys in 1995 and subsequent years were entered into a spreadsheet. For each year, summary statistics such as D_{50} (the median particle diameter) and D_{84} (the diameter which is greater than or equal to 84% of all particles in the sample) were calculated for each cross section and for each reach as a whole (pooling all samples). D_{84} is a commonly used statistic in fluvial hydraulic and sediment transport calculations and is often used to characterize bed roughness (e.g., Bathurst, 1978; Thorne and Zevenbergen, 1985; Grant et al., 1990).

9.6 Peak Flow Analysis

9.6.1 Determination of Historical Peak Flows at the Cross Section Sites

For each pair of consecutive cross section profile surveys (Table 9.2), channel adjustments inferred from the profile plots were assumed to be associated with the largest peak flow event that occurred during the interval between surveys. Since significant change is infrequent in this system and there are seldom multiple potentially channel-modifying events in any given year, it is reasonable as a first approximation to assume that any observed changes are associated with the largest peak flow event during the interval between consecutive surveys. The simplest and perhaps the most relevant measure of the magnitude or intensity of peak flow events for this purpose is the instantaneous peak discharge, which is readily available from stream gaging data.

The LOL site and the Mack Creek sites are fortunate to be located close to stream gages for which data are available over the entire length of the cross section record (Figure 3.1). For these study reaches, the gaging station data were assumed to accurately represent the hydrologic conditions experienced within the reach. For the MAC and LOL sites, the measured discharges at the Mack Creek and the Lookout Creek gages, respectively, were adjusted for the small difference in drainage area between the gage location and the study reach. For the MCC site, data from the Mack Creek gage (which is located at the upper end of the study reach) were used without area adjustment.

Peak discharges at the middle Lookout Creek and Cold Creek sites are less well known, because neither channel has a gage near the study reach (Figure 3.1). For these sites, proxy data based on the unit area discharge (discharge divided by drainage area) were obtained from the nearest or most comparable available stream gages. The unit area discharge from the Lookout Creek gage was used for the middle Lookout Creek site, which is located on 4th-order Lookout Creek roughly in the center of the watershed (Figure 3.1) and has a drainage area approximately one-half that of the lower Lookout Creek site (Table 9.1). The gage for WS 8 (Figure 3.1) was used as a discharge proxy for the Cold Creek study reach; WS 8 is roughly comparable to Cold Creek in drainage area and elevation (Tables 9.1 and 9.3). Although only 3 of the 5 stations (Lookout Creek, Mack Creek, and WS 8) were used directly to estimate flows at the cross section sites, discharge records for two additional "control" watersheds—WS 2 and WS 9—were also examined to assess the spatial variability of peak flow magnitudes. These stations were chosen because the watersheds they monitor (except for the Lookout Creek gage) are essentially undisturbed by logging, road-building or other land use activities.

9.6.2 FLOOD FREQUENCY ANALYSIS

Flood frequency analyses (Appendix D) were performed using data from the Lookout Creek, Mack Creek, and WS 8 gaging stations to estimate the frequency of peak flow events associated with channel changes observed at the cross section sites. Since the objective was to be able to relate cross section changes to the largest flood during the interval between consecutive (typically annual) surveys, the annual flood series (largest flood in each year) was used for this analysis rather than a partial duration series of all floods above a given threshold regardless of when they occur. Using an annual flood series also avoids the problem of having to decide whether closely spaced hydrograph peaks are independent events or not. Furthermore, the differences between recurrence intervals estimated using partial duration series and annual series are minor for the relatively infrequent events that are of greatest interest in this study (Haan, 1977).

Flood frequency analysis is a means of estimating, for any specified discharge x, the probability that this discharge will be equaled or exceeded within any given year—the *exceedance probability* of x. If the annual maximum discharge X is thought of as a random variable with a cumulative distribution function (CDF) $F_X(x) = p_x$, where $p_x = \Pr\{X \leq x\}$, then the exceedance probability associated with a discharge of x is $1\text{-}p_x$. The recurrence interval, or the expected average time interval between annual floods of magnitude x or greater, is $RI_x = 1/(1\text{-}p_x)$ (Haan, 1977). For a series of n annual maximum peak flow values, an empirical CDF can be constructed by plotting the magnitude of each event vs. its estimated exceedance probability. The remainder of the frequency analysis then consists of fitting a theoretical probability distribution function to the data.

The most commonly used estimator of exceedance probability, or plotting position as it is commonly called, is the Weibull plotting position, which is calculated as $m/(n+1)$, where m is the rank of the event from 1 (largest) to n (smallest) (Haan, 1977). The reciprocal of the plotting position for an event of magnitude x, or $(n+1)/m_x$, yields a point estimate of the recurrence interval RI_x of x. The ranked annual peak flow values and the corresponding Weibull plotting positions and estimated recurrence intervals for the annual maximum flood series for Lookout Creek, Mack Creek, and WS 8 are given in Appendix D, Table D.4.

The flood frequency analysis followed the procedure recommended by the U.S. Water Resources Council as described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). The Bulletin 17B method involves fitting a Log Pearson Type III (LP III) distribution to the observed peak flow data using a modified method of moments (Stedinger et al., 1993). The method is described in detail in Bulletin 17B and in standard hydrology references, and is not repeated here. Summary statistics from the annual peak flow series and parameter values used in fitting the LP3 frequency curve to the data are given in Appendix D, Table D.5.

Two potential outliers were identified in the annual flood series for Lookout Creek. The peak flow for WY 1977—which at 293 cfs (8.30 m^3/s) was less than half as large as the next smallest annual peak flow in the data set—was identified as a low outlier (Appendix D) and was removed from the data prior to fitting the LP3 frequency distribution in accordance with the Bulletin 17B protocol. The February 1996 flood peak for Lookout Creek was slightly above the high outlier threshold (Appendix D, Table D.5). Lacking a sound basis for treating this value as an historic flood (i.e., as the largest flood in N years, where N is greater than the record length n of measured flows), it was retained as part of the record as recommended in Bulletin 17B. No outliers were identified in the records for Mack Creek or WS 8.

9.7 Cross Section Change Analysis

The cross section data were analyzed using descriptive, semi-quantitative, and quantitative approaches. Descriptive methods (Section 8.3, Figure 8.4) were used to characterize channel response to different events and to address questions relating to between-site differences in the nature of channel response to a particular event, or between-event differences in the style of channel response at a site. A semi-quantitative, classification-based approach was used to answer questions pertaining to when detectable change in the channel cross-section profiles occurred and the frequency with which changes of different magnitude (minor, moderate, or substantial) occurred through time (Section 9.7.1). Classified cross section changes were used in conjunction with a logistic regression approach (Section 9.7.3) to assess the probability of channel adjustments of a given relative magnitude within each study reach relative to the magnitude of the largest flood during the interval between consecutive cross section surveys. In the quantitative approach (Section 9.7.2), cross section data were used to estimate the magnitude of scour and deposition at each profile location and relate this to the magnitude of imposed stress (e.g., peak discharge) during the interval between surveys.

9.7.1 SEMI-QUANTITATIVE ASSESSMENT OF CHANNEL RESPONSE

A visual classification-based approach was developed to summarize channel adjustments of various relative magnitudes at each cross section at the MAC, MCC, LOM, and the LOL sites. For a given cross section location, each pair of corrected, filtered, and scaled profiles from consecutive surveys (Table 9.2) represented one observation of channel change (or lack of change) at one location for one "event," which was assumed to correspond to the largest peak flow during the time interval between observations. These channel change observations were scored using the criteria shown in Table 9.4 (see Figure 9.16 for definition sketch). Examples of scored profile plots representing each of the four cases are presented in Figure 9.17. Response scores for each pair of consecutive surveys are tabulated for the LOL, LOM, MCC and MAC sites in Appendix E.

In Figure 9.17(a), the cross section response was negligible and was scored as 0. The pair of profiles in Figure 9.17(b) show scour over an interval of ≥ 0.1 channel widths with an amplitude of approximately 0.2 m, which meets the minimum criteria for a score of 1 (Table 9.4). In Figure 9.17(c), scour of ≥0.2 m over a distance of >0.2 channel widths is apparent, resulting in a score of 2. Figure 9.17(d) shows a typical example of a cross section response to the February 1996 flood, in which each of two large cross section changes meet one or both of the alternate criteria for a score of 3 (Table 9.4): a vertical change of bed elevation of ≥0.5 m over a distance of 0.2 channel widths or a vertical change of 0.3 m over a distance of 0.4 channel widths.

Table 9.4. Classification criteria for cross section response scores. See Figure 9.16 for definition sketch.

Score	Description	Criteria		
0	No significant detectable change			
1	Minor change	$\Delta z \geq 0.2$ m	and	$x_{int} \geq 0.1\ L'_{eff}$, or
		$\Delta z \geq 0.15$ m	and	$x_{int} \geq 0.2\ L'_{eff}$
2	Moderate change	$\Delta z \geq 0.4$ m	and	$x_{int} \geq 0.1\ L'_{eff}$, or
		$\Delta z \geq 0.2$ m	and	$x_{int} \geq 0.2\ L'_{eff}$
3	Substantial change	$\Delta z \geq 0.5$ m	and	$x_{int} \geq 0.2\ L'_{eff}$, or
		$\Delta z \geq 0.3$ m	and	$x_{int} \geq 0.4\ L'_{eff}$

[1] Δz is the average vertical distance between the channel bed/bank elevation in the profiles being compared and x_{int} is the fraction of the effective orthogonalized cross section length, L'_{eff} (see Figure 9.14), occupied by the feature or features. No more than 2 features were combined to meet the length criterion.

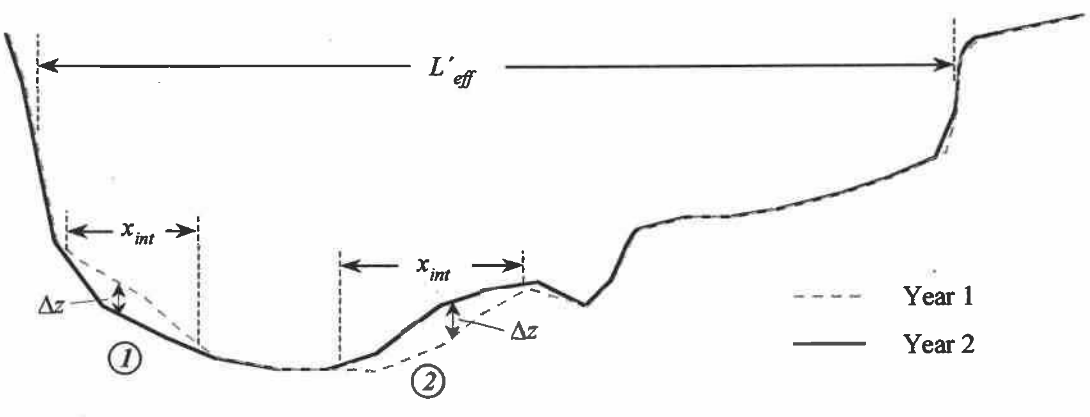


Figure 9.16. Definition sketch for visual cross section profile change classification scheme in Table 9.4. L'_{eff} is defined in Figure 9.14; Δz is the average vertical displacement between profiles within a particular erosional or depositional feature (e.g., 1 and 2, respectively) of length x_{int}.

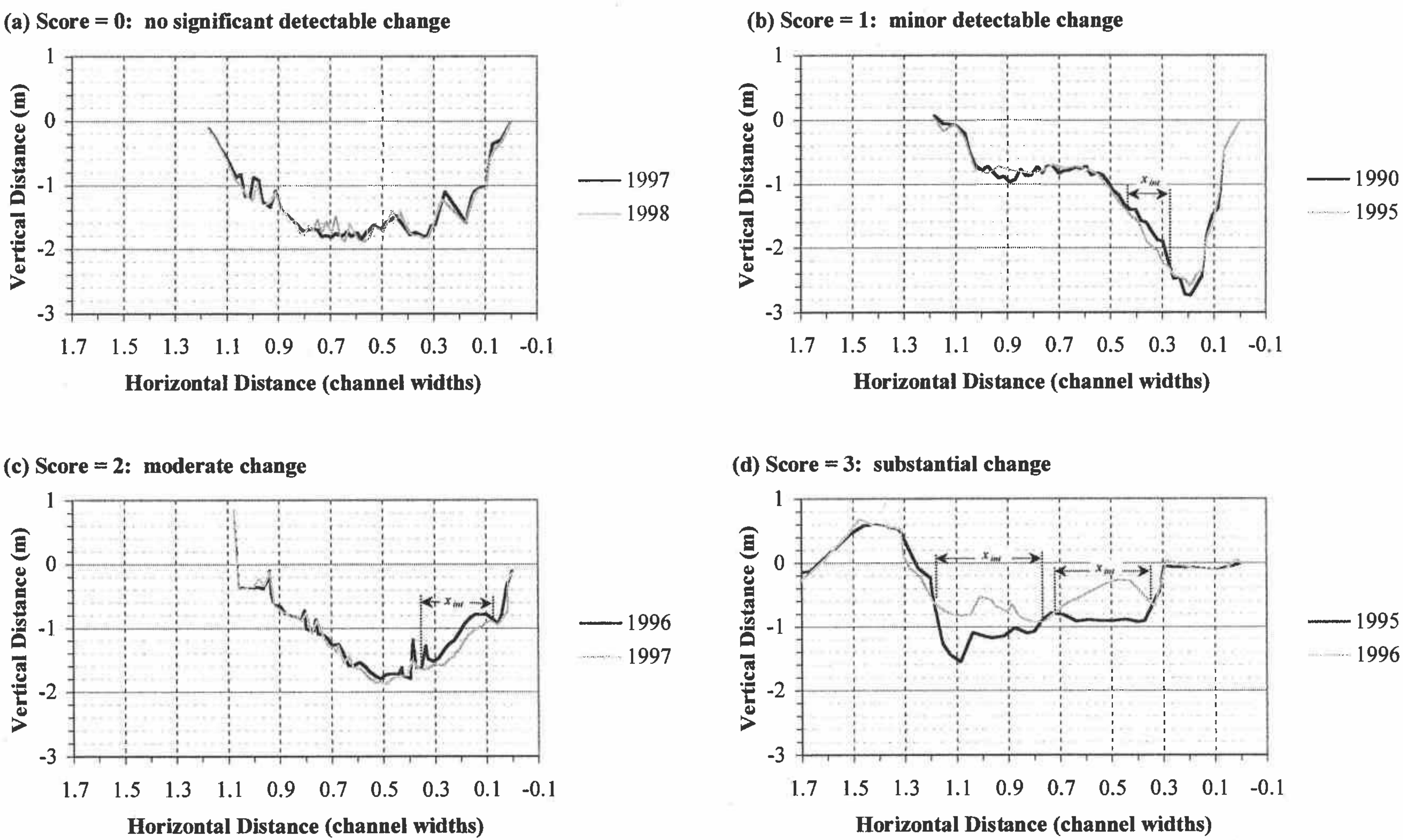


Figure 9.17. Examples of consecutive cross section profile pairs classified by degree of channel adjustment. (a) LOM site, XS 1, 1997-98; (b) LOL site, XS 11, 1990-95; (c) LOL site, XS 2, 1996-97; (d) MAC site, XS 3, 1995-96.

This classification scheme facilitates comparisons between the different study reaches despite the range of channel sizes represented. For example, scour to a depth of 20 cm across a 1-m width of channel would be relatively more significant at the MAC site, where it would represent approximately 10% of the average active channel floodway width, than it would be at the LOL site, where the same 1-m wide scour patch would represent only about 3.5% of the average channel floodway width. Scaling the cross section profiles by the active channel floodway width eliminates this disparity and allows visual classification of channel adjustments of comparable relative magnitude. However, the trade-off is that since the absolute horizontal resolution of the cross section profiles is the same at all sites—typically about 0.5 m—the resolution of the scaled profiles varies inversely with channel width. Thus, the Mack Creek profiles generally have fewer data points (hence, poorer resolution) than the Lookout Creek profiles, and the Cold Creek profiles have such poor resolution that they were excluded from this portion of the analysis.

A cross section response score of 1 corresponds to the smallest change that could be identified with reasonable confidence across the range of cross section profile resolution (e.g., Figure 9.17b). These are very minor changes that probably would not be evident to an observer in the field. Changes associated with a response score of 2 are somewhat larger but still relatively modest (Figure 9.17c); changes at the low end of this class might only be noticeable to an observer who is very familiar with the site or is equipped with detailed photographs of the prior channel condition. Changes corresponding to a response score of 3 (e.g., Figure 9.17d) would be immediately apparent to an observer even casually familiar with the site.

Using the cross section response scores, a summary statistic was developed for each event which characterizes the relative magnitude of channel response at the reach scale. The *cross section response index* was defined as the sum of the response scores for all the cross sections at a site for a given event divided by the maximum possible score (3 times the number of cross sections). The cross section response index is distinct from the cross section response probability or proportion, p (Section 9.7.3). By weighting larger responses (e.g., response score of 3) greater than small ones (e.g., response score of 1), the response index extracts more information from the classified cross section responses (Appendix E) than does the response probability, p. The cross section response index is simply the arithmetic average of the individual cross section response scores at a site for a given event normalized by the maximum possible response score to yield a value between 0 and 1.

It is important to note that the cross section response index does not reflect the full range of possible cross section response. While a score of 0 indicates that essentially no detectable change occurred at any of the cross sections at a site, a score of 1 indicates only that all cross sections exhibited fairly substantial changes (i.e., they exceeded the criteria for a response score of 3; see Table 9.4); any larger changes are not reflected by the response index score. That is, while the response index can effectively quantify the overall relative magnitude of channel change as measured by the cross sections over a wide range, it cannot discriminate between events for which cross section changes substantially exceed the maximum cross section response score criteria for a significant proportion of the cross sections at a site. This is only an issue with respect to the February 1996 flood, for which many cross section changes greatly exceeded the classification criterion for the maximum response score of 3, especially at the Lookout Creek sites.

9.7.2 Quantitative Assessment of Channel Response

Cross section changes were quantified for the floods of February 1996 and February 1986, the two flood events which produced detectable change at the greatest number of cross sections at each site (Appendix E). The minimum magnitude of channel change during the interval between consecutive surveys was estimated for each cross section location from the cross section profile data. Where the more recent profile lies below the earlier profile, scour is indicated (e.g., feature 1 in Figure 9.16); where the reverse is true, deposition is indicated (e.g., feature 2 in Figure 9.16). The areas labeled 1 and 2 in Figure 9.16 each represent a volume of sediment per unit distance normal to the page (i.e., cubic meters of sediment per meter of channel length) that was eroded from or deposited in the channel, respectively, during the interval between surveys. The magnitude of the channel response can be characterized by summing up all of the cross-sectional areas of scour and deposition across the channel. These are minimum values because the cross section profiles cannot detect areas of scour that were subsequently filled by new deposition or areas of deposition that were subsequently removed by channel scour during the interval between surveys.

Four measures of channel response were calculated for the 1986 and 1996 events (Appendix F). To facilitate comparison between study reaches, all values were scaled by the active channel floodway width, such that they can be thought of as representing an average depth of sediment eroded, deposited, or reworked. The four quantitative measures of channel response were:

1. mean scour depth—sum of cross sectional areas of scour divided by active channel floodway width,
2. mean fill depth—sum of cross sectional areas of deposition divided by active channel floodway width.
3. mean reworked depth—the sum of total scour and total deposition divided by active channel floodway width, and
4. net bed elevation change—total deposition minus total scour; divided by active channel floodway width; positive values indicate net deposition while negative values indicate net scour.

9.7.3 Logistic Regression Analysis

Logistic regression was used to examine the relationship between cross section change (dependent variable) and applied stress (independent variable) over time at each reach. Logistic regression is a useful technique for analyzing the relationship between a binary or binomial response variable and one or more continuous and/or categorical explanatory variables (Ramsey and Schafer, 1997). The dependent variable was the proportion, p, of cross sections at a site exhibiting detectable change between consecutive surveys. It can be thought of either as the probability that a channel response will be observed for randomly selected cross section within the reach being tested (response probability) or as the proportion of the total reach length in which a channel response was observed. The independent variable was a measure of the magnitude of the largest peak flow event during the interval between surveys, measured as unit area discharge, Q^*, or estimated recurrence interval, *RI*.

The logistic regression analysis was undertaken to answer two questions at each site:

1. How rapidly does p increase with increasing event magnitude? Does the transition from low response probability (say, $p < 0.10$) to high response probability ($p > 0.90$) occur abruptly, over a narrow range of Q^* or *RI*, (i.e., a threshold-like response, as in Figure 8.5, curve 1) or more gradually, over a wide range of Q^* or *RI* (e.g., Figure 8.5, curve 3)?
2. What magnitude of event Q^* or return period *RI* is the associated with a given response probability, p (e.g., Q_{50}, Figure 8.5)?

The logistic regression analysis was also used to address two additional questions about similarities or differences between the cross section sites:

3. Are there significant differences between sites in the slope of the response curve (e.g., Figure 8.5, curve 1 vs. curve 2)?
4. Are there significant differences between sites in the event magnitude associated with a given response probability p (e.g., the horizontal distance between curves 1 and 3 in Figure 8.5 for any specified value of p)?

9.7.3.1 Logistic Regression Theory and Model

If m binary responses are a random sample from a population of binary responses with population proportion p, then their sum Y has the *binomial*(m,p) probability distribution (Ramsey and Shafer, 1997). The classified individual cross section responses in this study can be treated as binary variables, taking on values of one (changed) or zero (unchanged). Then for each cross section site, the sum y_i of the m_i binary cross section responses for the ith pair of consecutive survey dates can be treated as one realization of a random variable Y_i drawn from a binomial(m_i,p_i) distribution, where $p_i = Y_i/m_i$ is the unknown population proportion of 1's among the binary responses of a hypothetical population of potential cross sections at the site, and the observed sample proportion $p_i' = y_i/m_i$ is our estimate of the population proportion. (Note that p_i and p_i' are also the population and sample means, respectively, of the binary responses).

A generalized linear model (GLM) is a probability model in which some function g of the mean η of the response variable Y is estimated as a linear function of a set of values $\mathbf{x} = \{x_1, x_2, \ldots, x_k\}$ of some set of explanatory variables $\{X_1, X_2, \ldots, X_k\}$. This can be written as

$$g(E(Y|\mathbf{x}) = g(\mu|\mathbf{x}) = \beta_0 + \beta_1 X_1 + \ldots + \beta_k X_k = \eta(\mathbf{x}) \qquad (9.1)$$

where g is known as the *link* function and $\eta(\mathbf{x})$ is called the *linear predictor* (MathSoft, 1997a). In the case of logistic regression, the link function is the *logit* function:

$$g(p) = \text{logit}(p) = \ln\left(\frac{p}{1-p}\right) \qquad (9.2)$$

In a logistic regression context, the mean of the binary responses is commonly designated by p or π rather than μ to emphasize that it is a probability or proportion. In our case, it is the binomial proportion $p_i = Y_i/m_i$, not the individual binary responses, that constitute the response variable of interest. For each cross section site, the sample size n is the number of pairs of consecutive survey dates (i.e., the number of survey dates minus one, see Appendix E), *not* the binomial denominator m_i.

The statistical package S-Plus (MathSoft, 1997b) was used to perform the logistic regression analysis. In S-Plus, a logistic regression is specified as a GLM (Equation 9.1) with the logit function (Equation 9.2) as the link function and a variance function defined by

$$\text{Var}(Y) = \phi m p(1 - p) \qquad (9.3)$$

[or equivalently, $\text{Var}(Y/m) = \phi p(1\text{-}p)$], where ϕ is a *dispersion parameter* that for logistic regression is typically set to be 1. S-Plus solves the GLM using the method of maximum likelihood estimation to estimate the values of the parameters β_j in accordance with standard statistical theory (e.g., McCullagh and Nelder, 1989). Setting the dispersion parameter $\phi = 1$ is equivalent to assuming Y is binomially distributed. This assumption can be relaxed somewhat allowing ϕ to vary to account for under- or over-dispersion of the data relative to a binomial distribution, an approach known as quasi-likelihood estimation. The quasi-likelihood approach was used in this analysis.

The logit function is also known as the log-odds function, because the term on the right-hand side of Equation 9.2 is the natural logarithm of the odds of a "yes" result (observing change) vs. a "no" result (observing no change) in a single binary response (Ramsey and Shafer, 1997). For example, if 4 out of a sample of 10 cross sections exhibited detectable change, y_i would be 4, m_i would be 10, and hence the estimated probability of observing change at any single section, p_i', would be 0.4. (The prime notation is used here to distinguish observed sample proportion p_i' from the unknown population proportion p_i). However, the estimated *odds* of observing a change would be 2:3 ($p_i'/[1- p_i']$, or 0.4/0.6). That is, a cross section selected at random from the sample would be two-thirds as likely to exhibit detectable change as not, or conversely, it would be 50% more likely (odds of 3:2) *not* to show detectable change as to show such change. Note that *odds* are a ratio of the probabilities of two possible outcomes (change vs. no change), which is different from the *probability* of a particular outcome, which is given by the binomial proportion y_i/m_i, or 0.4 in this example. The probability of an outcome can range between 0 and 1, while the odds of that outcome can vary between 0 and infinity.

The relationship between probability or proportion and odds is illustrated in Figure 9.18, which shows p as a function of the linear predictor η. If logit(p) = η (as in Equation 9.1 when the link function g is the logit function), then

$$p = e^{\eta}/(1+e^{\eta}) \qquad (9.4)$$

This is the logistic function, which is the inverse of the logit function and is the form of the predictions from a logistic regression model back-transformed to the scale response variable Y/m. For a unit increase in η from η_1 to η_2, the odds increase by a fixed factor of e (i.e., approximately 2.718), but p increases by different amounts depending on the values of η_1 and η_2. More generally, for a change in η of any fixed increment δ, the odds will change by e^{δ}. Hence, for a change Δx in the value of a

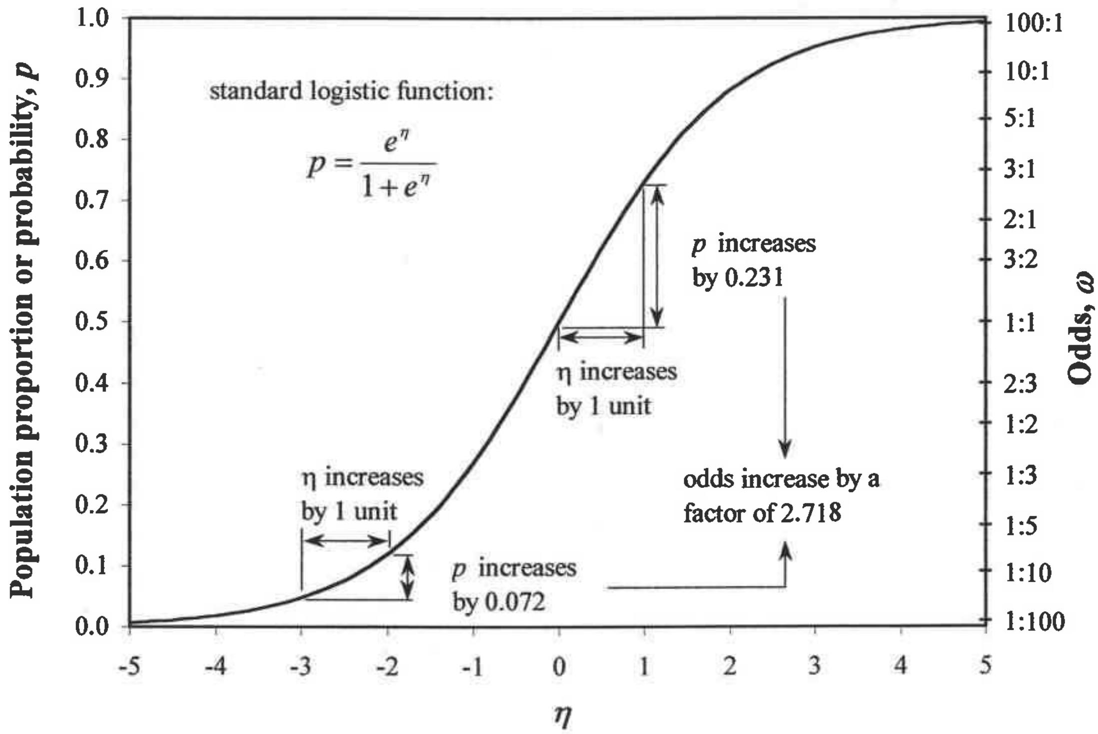


Figure 9.18. The standard logistic function and the relation between the probability and odds for an event occurring. The logistic function is the inverse of the logit function and gives the probability p of an event as a function of the value of the linear predictor η in a logistic regression model. The odds, ω, are the ratio of the probability p that an event will occur to the probatility 1-p that it will not occur. (Modified from Ramsey and Shafer [1997].)

single explanatory variable X_j while holding all other explanatory variables constant in Equation 9.1 (for $1 \le j \le k$), η would change by $\delta = \beta_j X_j$ and the odds would change by $e^{\delta} = e^{\beta_j \Delta x}$. The quantity $e^{\beta_j \Delta x}$ is the known as *odds ratio* associated with a change Δx in the explanatory variable X_j. Note that the odds ratio would be greater than 1 (i.e., an increase) for $\delta >$ 0 and less than one (a decrease) for $\delta < 0$.

A simple logistic regression model to relate response probability p to a single response variable, say Q^*, can be expressed as

$$\text{logit}(Y/m) = \beta_0 + \beta_1 Q^*_1 \qquad (9.5)$$

The regression parameters in this model relate explicitly to the conceptual model of Section 8.4 and the questions of interest set forth at the beginning of this section.

Figure 8.5 shows several hypothetical channel response curves which could be modeled by Equation 9.5. The slope parameter β_1 in this model characterizes the shape of the response curve, with low values corresponding to a gradual response (curve 3 in Figure 8.5) and high values corresponding to an abrupt or threshold-like response (curves 1 and 4 in Figure 8.5). (Also, as discussed above, β_1 gives the multiplicative increase in the odds of observing change for a unit increase in Q^*).

The position of the response curve on the horizontal axis in Figure 8.5 is a function of both the slope and intercept parameters (β_1 and β_0, respectively) in Equation 9.5. Specifically, the value of Q^* associated with a 50% change probability, Q^*_{50}, is equal to $-\beta_0/\beta_1$. To see this, note that when $p_i = Y_i/m_i = 0.5$, the left-hand side of Equation 9.5 becomes zero (because logit(0.5) = ln [0.5/(1-0.5)] = ln 1 = 0). Then solving for Q^* yields $-\beta_0/\beta_1$. In Figure 8.5, curves 1 and 4 have the same value of β_1 but different values of β_0 (such that $-\beta_0/\beta_1$ for curve 4 is greater than for curve 1), while curves 1 and 2 have different values of β_1, but the ratio of the two parameters (β_0/β_1) is the same.

For purposes of comparing responses between two sites, it is more useful to formulate the logistic regression model as

$$\text{logit}(Y/m) = \beta_0 + \beta_1 Q^*_i + \beta_2 Site + \beta_3\, Q^*_i \times Site \qquad (9.6)$$

where *Site* is an indicator variable taking on the values 0 for one site (the *reference site*) or 1 for the other site. The slope and intercept parameters for the reference site are the same as for the single-site model, β_1 and β_0 respectively, while the corresponding parameters for the second site are given by $\beta_1 + \beta_3$ and $\beta_0 + \beta_2$, respectively. β_2 and β_3 are *site contrast* parameters and measure the between-site differences in the slope and intercept parameters, respectively. β_2 by itself has no useful interpretation. However, β_3 is a measure of the degree to which one site exhibits a more threshold-like response than the other (e.g., the difference between curves 1 and 2 in Figure 8.5). A test whether the response curves for the two sites are significantly different in this regard is equivalent to a test of the hypothesis that $\beta_3 = 0$.

It is not possible to formulate a test for whether Q^*_p differs between sites in terms of a hypothesis about a single model parameter, since this difference depends upon both slope and intercept parameters as well as the value of p. However, S-Plus does calculate a standard error for the predicted values of p from the logistic regression, allowing the calculation of an approximate 95% confidence interval (± 2 standard errors) for the predicted response curve. For those values of p for which the predicted response curves for two sites lie outside each other's 95% confidence bands, the difference in Q^*_p values can be inferred to be statistically significant at an approximate significance level of 0.05 or less.

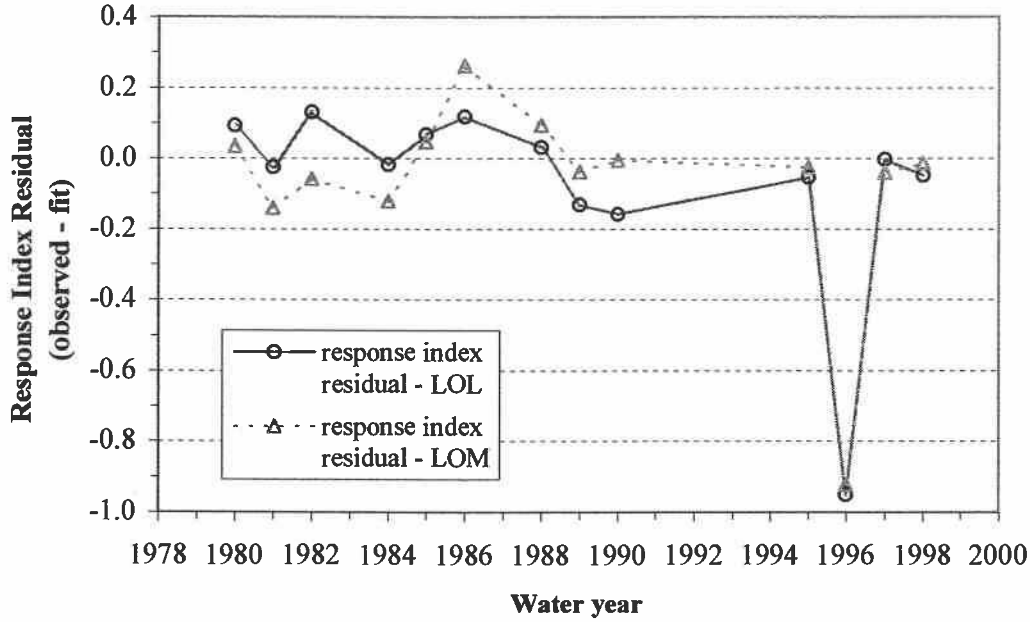
9.7.3.2 Model Assumptions

The logistic regression approach used here has the following built-in assumptions:

1. the cross sections at each site comprise a representative random sample of potential cross sections at that site;
2. the probability p corresponding to any given value of Q^* is constant through time (i.e., stationary); and
3. the cross section responses are independent of each other.

As is common in statistical analyses of real-world data, none of these assumptions are strictly true, so the question with respect to the validity of the approach becomes one of how serious are the violations, and how does this affect the interpretation of the results? The consequences of violating the first assumption are serious only if the cross section locations used for a given site are biased or otherwise unrepresentative of the reach as a whole, which is not believed to be the case. The second assumption is relevant to a question posed in this study—whether channel sensitivity to disturbance changes over time, particularly in the aftermath of a major flood. Because past disturbances set the antecedent conditions for future disturbances, it is important to check this assumption. Of particular interest is whether there are any trends through time in the relationship between Q^* and cross section response as measured by either p or the cross section response index. The residuals from a

(a) Lookout Creek sites



(b) Mack Creek sites

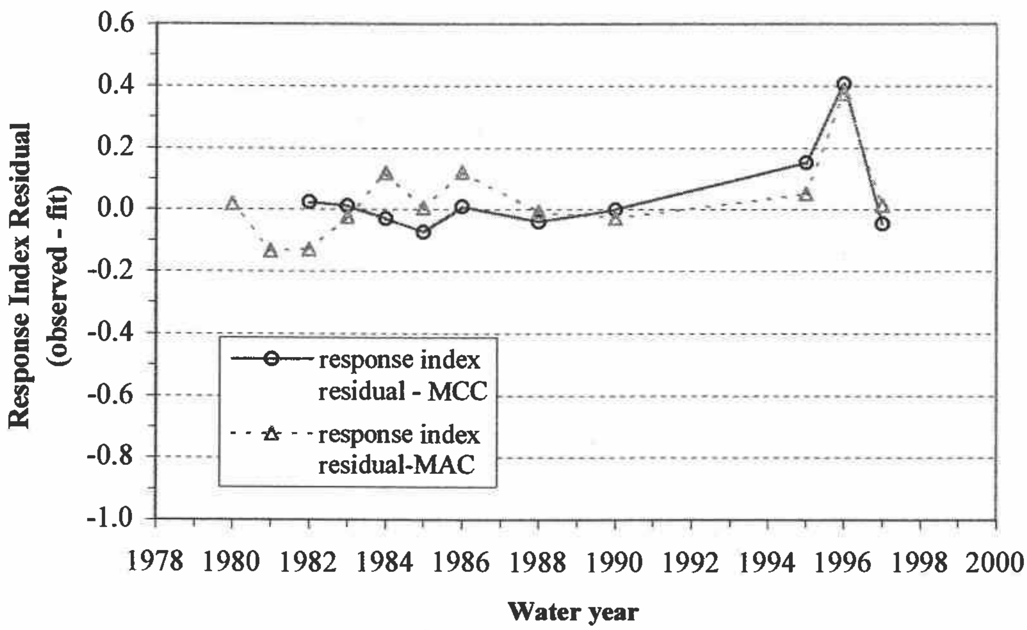


Figure 9.19. Residuals from regression of cross section response index scores vs. Q^* plotted by water year: (a) Lookout Creek sites, and (b) Mack Creek sites. The 1996 flood was omitted from the regression model.

regression of cross section response index vs. Q^* shows no sign of a trend over time for any of the cross section sites (Figure 9.19), suggesting that the assumption of stationarity is valid.

Lack of independence (assumption no. 3) is the issue of greatest concern in this analysis. Cross section responses are clearly spatially correlated for large events such as the 1996 flood, where reach scale channel responses were observed, at least at the Lookout Creek sites (see Sections 10.2.3 and 10.2.4). However, spatial autocorrelation is much less of an issue with respect to cross section responses to the smaller events which make up the bulk of the data set. Use of the quasi-likelihood approach also helps mitigate potential effects of lack of independence between cross sections.

10 Results

This chapter presents the major findings of this investigation into the frequency, magnitude, and spatial patterns of channel response to peak flows in 2nd to 5th-order streams within the Lookout Creek watershed. Section 10.1 discusses historical peak flows within the Andrews Forest and presents the results of a flood frequency analysis for streams including the cross section study sites. The magnitude and styles of channel and riparian response to the floods of February 1996 (25-100+ year recurrence interval) and February 1986 (6-12 year recurrence interval) at the five cross section sites are described and compared in Section 10.2. Section 10.3 discusses the relationship between peak flow magnitude and the magnitude channel response at the reach scale as measured by the cross sections. Finally, Section 10.4 analyzes the relationship between peak flow magnitude or recurrence interval and the probability of observing a channel response based on the cross section monitoring data, and compares the frequency of observed channel disturbance by peak flows at the study reaches.

10.1 Peak Flow Analysis

The following sections present the results of an analysis of historical peak flows which drive channel change in the study area. Section 10.1.1 describes the historical peak flow record for several gaging stations within the study area and discusses the implications of this record with respect to the analysis of cross section changes that comprises the primary focus of this chapter. Section 10.1.2 presents the results of a flood frequency analysis for selected gaging stations. Finally, Section 10.1.3 discusses uncertainties associated with the estimated peak discharge for the February 1996 flood in Lookout Creek.

10.1.1 HISTORICAL PEAK FLOWS

Analysis of peak flows in Lookout Creek and smaller tributary watersheds within the Andrews Forest reveals that during the period 1978-1995 (i.e., all but the last three years of the cross-section record) there were few large peak flow events relative to the entire period of record (water years 1950-98) for the Lookout Creek gaging station. Comparisons between gaging stations across the range of drainage area and elevation within the study area reveal generally similar patterns of peak flows, with both the magnitude (in terms of unit area discharge) and rank of events strongly correlated between stations. However, the frequency of events exceeding a given threshold unit area discharge shows substantial variation between sites.

Two major floods stand out in the record of mean daily discharge in Lookout Creek (WY 1950-98): the flood of December 21-27, 1964 and the flood of February 6-10, 1996 (Figure 10.1[a]). These floods were of similar magnitude, with estimated recurrence intervals of >80 years (see Section 10.1.3), and both were more than 60 percent higher than the next largest flood. Large peak flow events were rare during the 23-year period from 1973-1995 (Figure 10.1[a], [b]): only seven of the 27 recorded peak flows greater than 50 m^3/s occurred during this period. During the first five years of this period (1973-77), no peak flows exceeded 50 m^3/s, and during the last nine years (1987-95) only two exceeded 50 m^3/s, but neither of these exceeded the mean annual flood (i.e., the average size of the annual maximum instantaneous peak flow) of 56.1 m^3/s (Figure 10.1[b]).

Large peaks were rare during most of the 20-year period over which the cross sections were monitored. Only three of the ten peak flows exceeding 75 m^3/s (2650 cfs) occurred during this period (Figure 10.1[b]). During the 17 years following the installation of the first reference cross sections in the summer of 1978, only three peak flow events exceeded the mean annual flood (in 1981, 1984, and 1986). During the next two years, five distinct peak flows exceeded the mean annual flood, four of them during WY 1997 (on November 19th and December 4th and 26th, 1996, and January 31st, 1997).

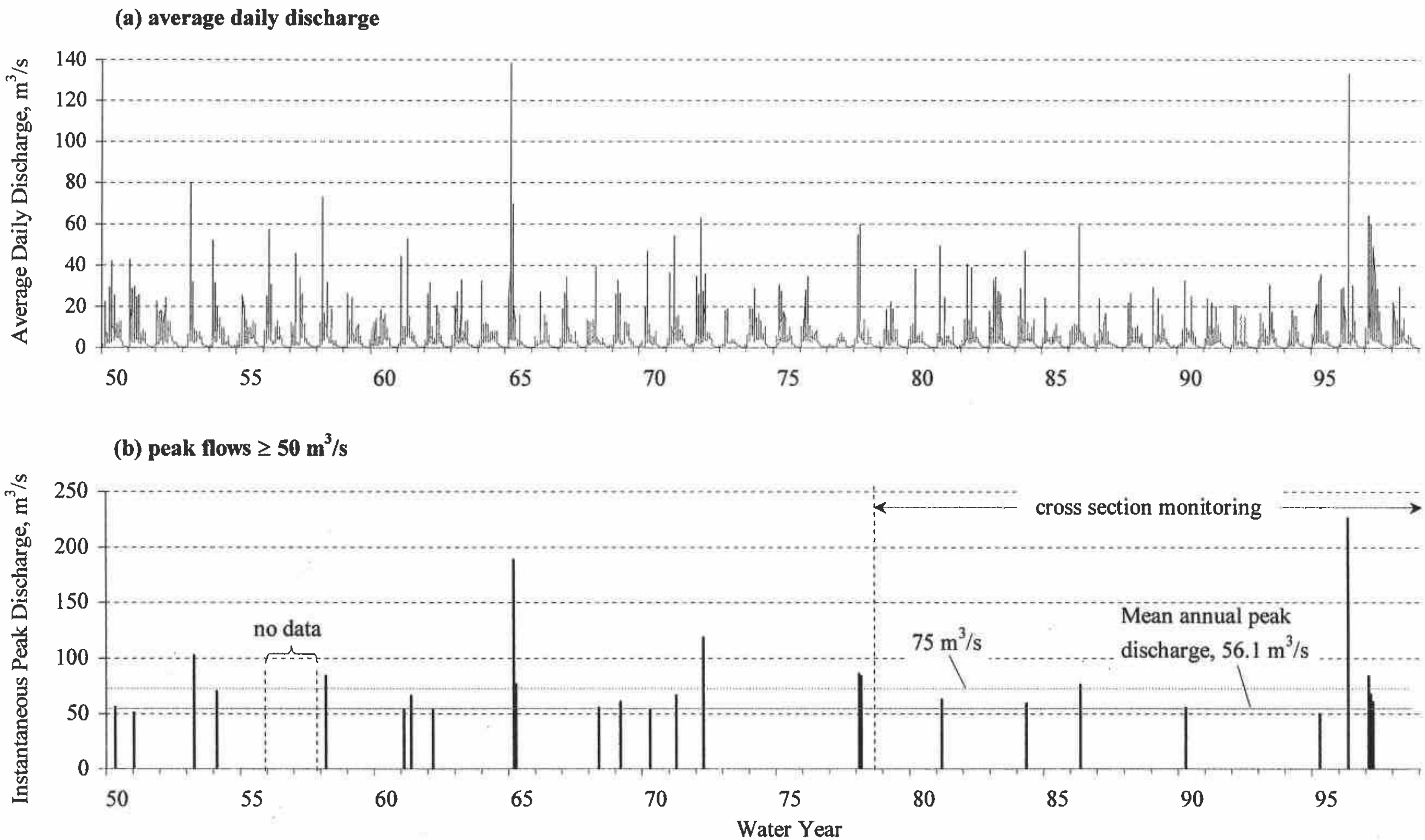


Figure 10.1. Lookout Creek discharge for water years 1950-1998: (a) mean daily discharge, and (b) peak flows exceeding 50 m^3/s (1766 cfs).

Large peak flow events were generally consistent between Lookout Creek and the four small "control" watersheds used in this study for the 20-year cross section monitoring period from October 1978 to October 1998 (Figure 10.2). Despite differences in drainage area spanning nearly three orders of magnitude (Table 9.3), the records show similar patterns in terms of the timing and relative magnitudes of peak flow events exceeding a unit area discharge of 0.75 $m^3/s/km^2$ (equivalent to 46.8 m^3/s or 1,650 cfs at the Lookout Creek gage). Peak flow events exceeded 0.75 $m^3/s/km^2$ at all five stations on seven occasions: during water years 1981, 1982, 1984, 1986, 1996, and 1997 (2 events) (Figure 10.2). Less than 25% of peak flows greater than 0.75 $m^3/s/km^2$ occurred during the half of the monitored period between the floods of February 1986 and February 1996 (Figure 10.2). The consistency of the record among sites and the relative quiescence of the February 1986 to February 1996 period are also evident when the records are expressed as the annual peak unit area discharge Q^* at each of the cross section sites (Figures 10.3, 10.4; Table 10.1).

Floods with estimated return periods greater than five years occurred only four times during the cross section monitoring period (Table 10.1; the WY 1978 peak flows occurred before the first cross section survey in summer 1978), and floods of this magnitude occurred at all five sites only three times: 1986, 1996, and 1997. It is clear from Figure 10.4 that Q^* magnitudes are strongly correlated between sites. This between-site correlation in Q^* is strong for all events (Figure 10.5), although the estimated discharge values for Lookout Creek in December 1964 and February 1996 are anomalously high (Figure 10.5[a] and [b]). These large floods were relatively larger events in Lookout Creek than in the smaller watersheds. Despite the between-site correlation in Q^* values, some basins (e.g., WS 9 and Mack Creek) produced large flood peaks ($Q^* > 0.75$ $m^3/s/km^2$) substantially more frequently than others (e.g., WS 8; Figure 10.2).

The historical peak flow analysis has several implications for interpretation of the cross section monitoring data. First, the cross section data may exhibit smaller and less frequent changes in the monitored period than during an average or wetter-than-average period. Second, more frequent cross section changes would be expected before 1987 and after 1995 than in the intervening years. Third, the synchronous

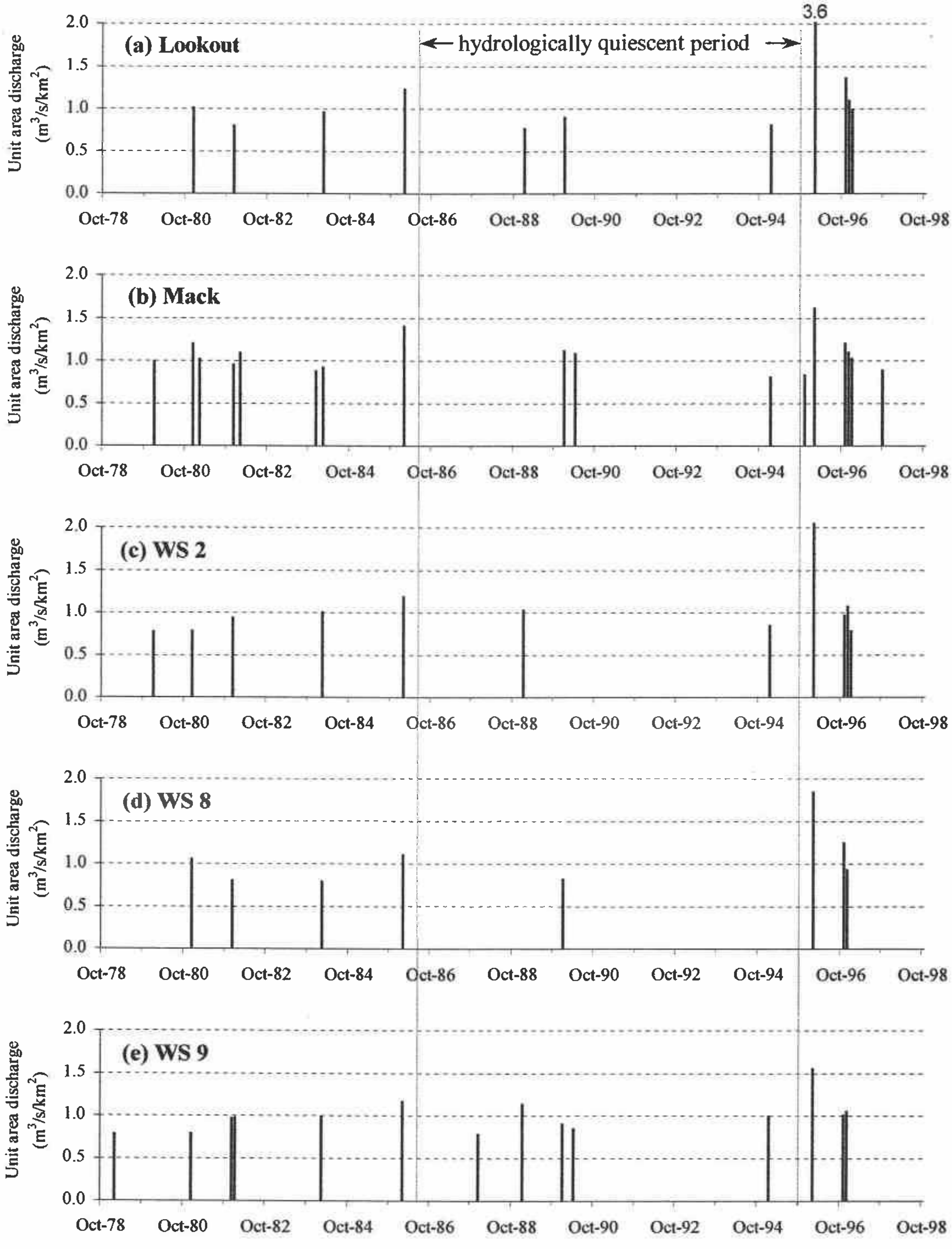


Figure 10.2. Peak flows exceeding 0.75 $m^3/s/km^2$ (equivalent to 46.8 m^3/s or 1,650 cfs at Lookout Creek gauge) during water years 1979–1998 in Lookout Creek and selected small "control" watersheds in the H.J. Andrews Experimental Forest. The hydrographs are arranged in order of decreasing drainage area, which spans a range of nearly 3 orders of magnitude (see Table 9.3).

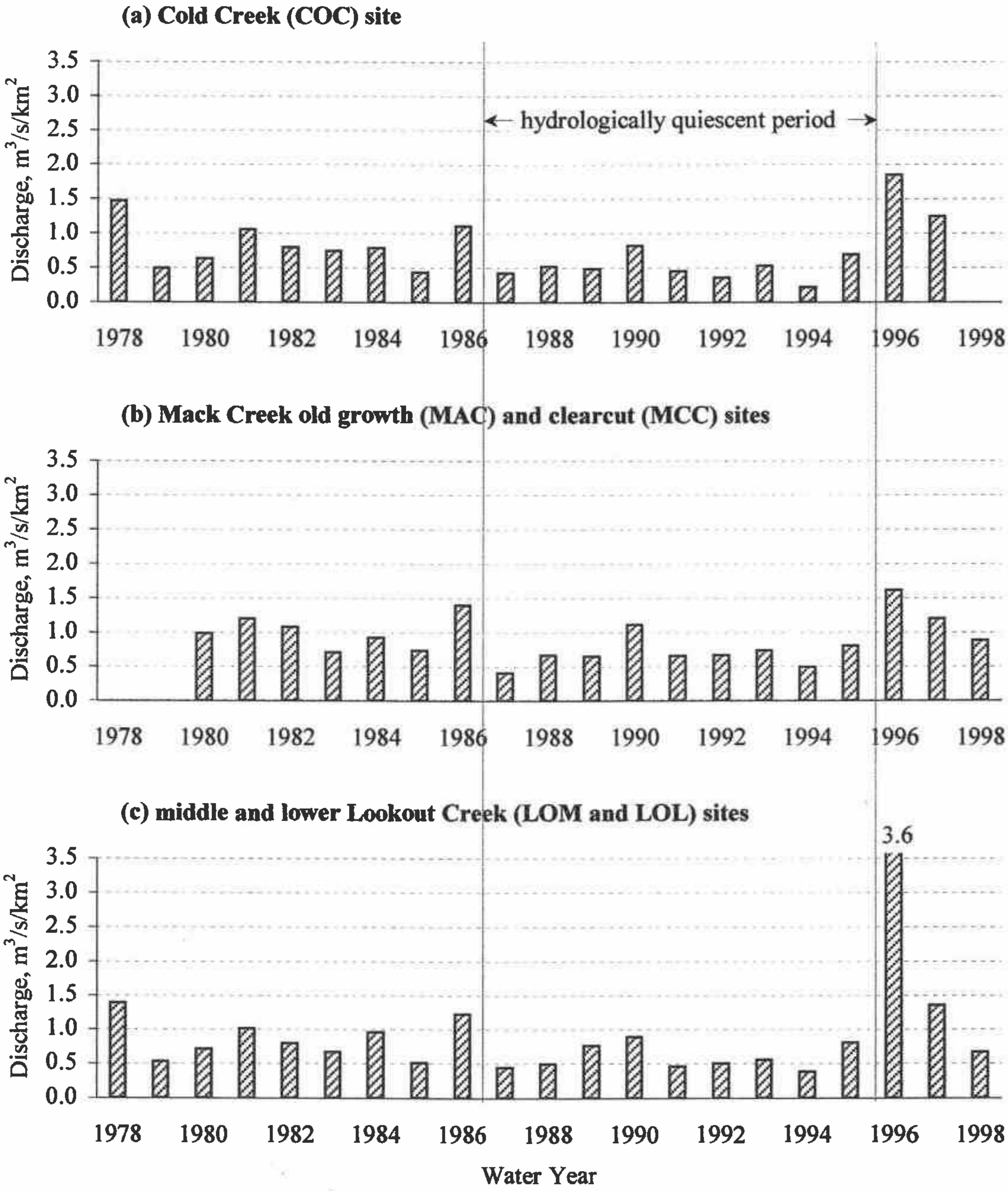


Figure 10.3. Estimated annual maximum instantaneous peak unit area discharge at cross section site locations, 1978-1998: (a) Cold Creek (COC) site, (b) Mack Creek old growth (MAC) and clearcut (MCC) sites, (c) middle and lower Lookout Creek (LOM and LOL) sites.

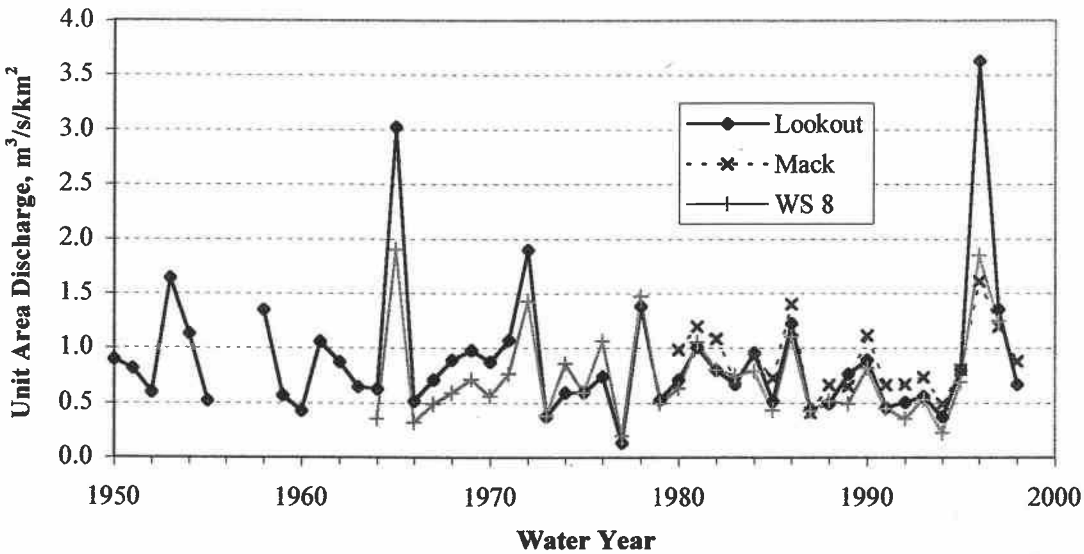


Figure 10.4. Annual peak unit area discharge, Q^*, at selected gaging stations.

timing and consistent relative magnitude or rank of peak flow events across sites allows unbiased comparisons among them, and it implies that between-site differences in cross section response may be attributable to site characteristics.

10.1.2 Flood Frequency Analysis

In terms of annual maximum instantaneous unit area discharge values, Q^*, Lookout and Mack Creeks were not significantly different from each other (2-sided p-value of 0.97 from a paired t-test), but annual Q^* values for both Lookout and Mack Creeks *were* significantly different from (greater than) those at WS 8 (2-sided p-values 0.01 and 0.0004, respectively). Average annual Q^* values for Lookout Creek, Mack Creek, and WS 8 for the period 1980-1998 (the Mack Creek gage began operation in 1980) were 0.88, 0.89, and 0.73 $m^3/s/km^2$, respectively. The values of Q^* as well as the annual peak discharge values in m^3/s for the Lookout Creek, Mack Creek, and WS 8 gaging stations are listed in Appendix D.

Table 10.1. Annual maximum instantaneous peak flows and estimated recurrence intervals (RI) for cross section sites, WY 1978-1998. Values in **boldface** indicate events for which the estimated RI is 5 years or greater.

	Discharge, m^3/s					Unit Area Discharge, $m^3/s/km^2$					Estimated Recurrence Interval, yr				
WY	**LOL**	**LOM**	**MCC**	**MAC**	**COC**	**LOL**	**LOM**	**MCC**	**MAC**	**COC**	**LOL**	**LOM**	**MCC**	**MAC**	**COC**
1978	**85.1**	**43.8**			**1.04**	**1.38**	**1.38**			**1.47**	**7.7**	**7.7**			**14.0**
1979	32.4	16.7			0.35	0.53	0.53			0.49	1.3	1.3			1.5
1980	43.6	22.4	5.73	5.54	0.45	0.71	0.71	0.99	0.99	0.63	1.8	1.8	3.1	3.1	2.0
1981	62.0	31.9	**6.94**	**6.72**	**0.75**	1.01	1.01	**1.20**	**1.20**	**1.05**	3.4	3.4	**6.2**	**6.2**	**5.4**
1982	48.9	25.1	6.28	6.08	0.56	0.79	0.79	1.08	1.08	0.79	2.2	2.2	4.2	4.2	2.9
1983	41.0	21.1	4.10	3.97	0.53	0.67	0.67	0.71	0.71	0.74	1.7	1.7	1.5	1.5	2.6
1984	58.6	30.2	5.34	5.16	0.56	0.95	0.95	0.92	0.92	0.79	3.1	3.1	2.5	2.5	2.8
1985	31.5	16.2	4.23	4.10	0.30	0.51	0.51	0.73	0.73	0.43	1.3	1.3	1.5	1.5	1.3
1986	**75.4**	**38.8**	**8.13**	**7.87**	**0.78**	**1.22**	**1.22**	**1.40**	**1.40**	**1.10**	**5.5**	**5.5**	**12.1**	**12.1**	**6.1**
1987	27.1	13.9	2.37	2.30	0.30	0.44	0.44	0.41	0.41	0.42	1.1	1.1	1.0	1.0	1.3
1988	30.4	15.7	3.86	3.73	0.37	0.49	0.49	0.66	0.66	0.51	1.2	1.2	1.4	1.4	1.6
1989	46.9	24.1	3.77	3.65	0.34	0.76	0.76	0.65	0.65	0.48	2.0	2.0	1.3	1.3	1.5
1990	54.7	28.2	6.46	6.25	0.58	0.89	0.89	1.11	1.11	0.82	2.7	2.7	4.5	4.5	3.0
1991	28.2	14.5	3.83	3.71	0.32	0.46	0.46	0.66	0.66	0.44	1.2	1.2	1.4	1.4	1.4
1992	31.0	15.9	3.88	3.75	0.25	0.50	0.50	0.67	0.67	0.35	1.2	1.2	1.4	1.4	1.2
1993	34.1	17.5	4.24	4.10	0.38	0.55	0.55	0.73	0.73	0.53	1.4	1.4	1.6	1.6	1.6
1994	23.1	11.9	2.85	2.75	0.16	0.38	0.38	0.49	0.49	0.22	1.1	1.1	1.1	1.1	1.0
1995	49.4	25.4	4.66	4.51	0.49	0.80	0.80	0.80	0.80	0.69	2.2	2.2	1.8	1.8	2.2
1996	**223.3**	**114.9**	**9.35**	**9.05**	**1.31**	**3.63**	**3.63**	**1.61**	**1.61**	**1.85**	**176.7**	**176.7**	**23.5**	**23.5**	**29.1**
1997	**83.2**	**42.8**	**6.94**	**6.72**	**0.88**	**1.35**	**1.35**	**1.20**	**1.20**	**1.24**	**7.3**	**7.3**	**6.2**	**6.2**	**8.4**
1998	41.0	21.1	5.11	4.94		0.67	0.67	0.88	0.88		1.7	1.7	2.2	2.2	

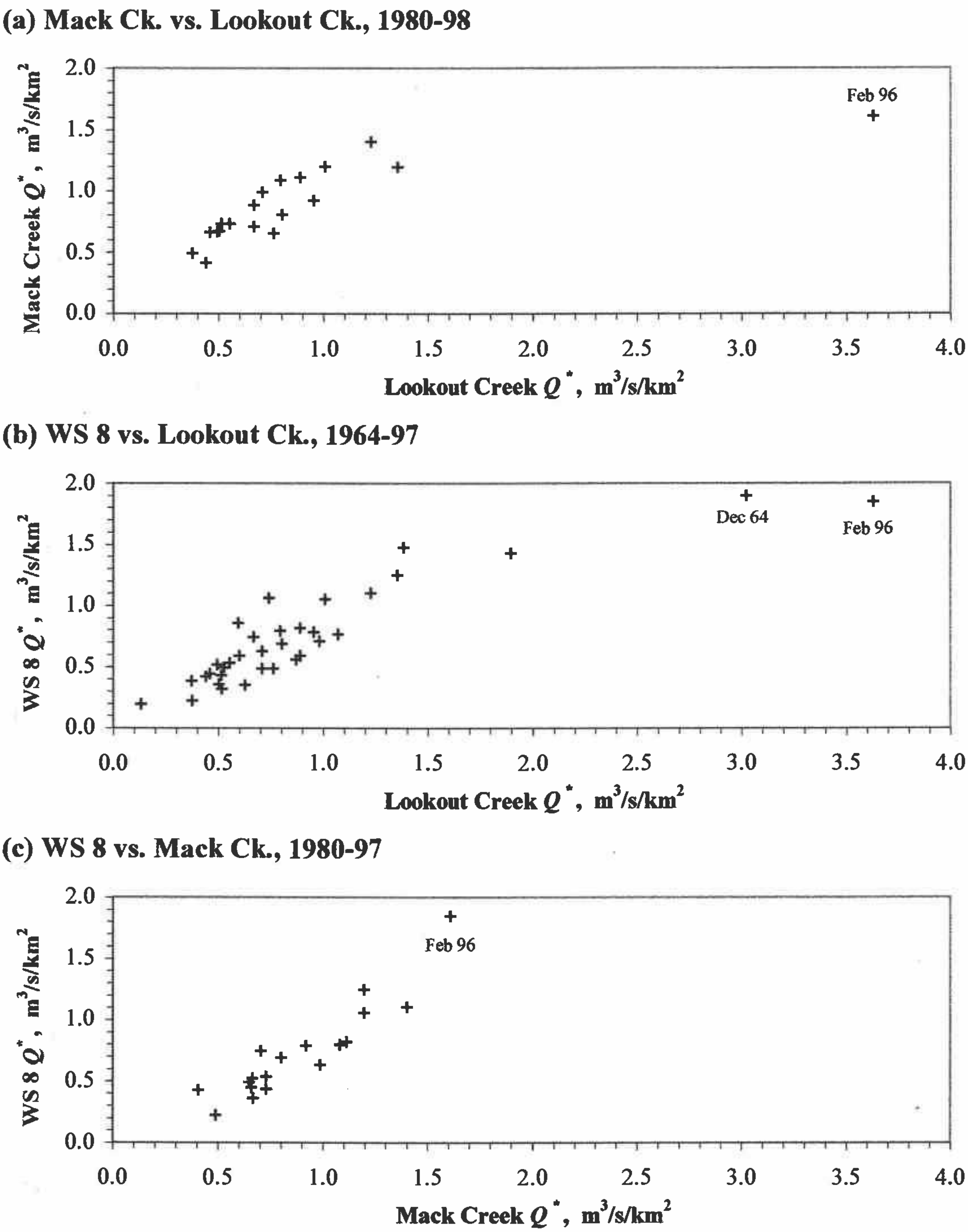


Figure 10.5. Scatterplots of magnitude of annual peak flows (as unit area discharge) for selected gaging station pairs: (a) Mack Ck. vs. Lookout Ck., 1980-98; (b) WS 8 vs. Lookout Ck., 1964-97; (c) WS 8 vs. Mack Ck., 1980-97. Major floods of Dec. 1964 and Feb. 1996 were relatively larger events in Lookout Ck. than in Mack Ck. and WS 8, and thus appear as outliers in plots (a) and (b).

The fitted flood frequency curves for Lookout Creek and WS 8 are very similar in shape but offset in position (Figure 10.6; see also Appendix D, Figures D.1 through D.3). That is, the frequency of peak flow events at both sites appears to decrease with increasing peak flow magnitude at about the same rate, but peak flows of any specified magnitude occur more frequently in Lookout Creek than in WS 8. The frequency curve for Mack Creek, on the other hand, is significantly flatter in shape, indicating that the frequency of peak flow events decreases more rapidly with increasing discharge in Mack Creek than in Lookout Creek or WS 8 (Figure 10.6). Peak flows less than about 1 $m^3/s/km^2$ are more frequent in Mack Creek than in Lookout Creek, while larger peak flows are more frequent in Lookout Creek than in Mack Creek. Similarly, peak flows less than about 1.4 $m^3/s/km^2$ appear to be more frequent in Mack Creek than in WS 8, while larger flows are more frequent in WS 8 than in Mack Creek.

Based on the approximate 90% confidence intervals for the frequency curves, peak flows less than about 0.7 $m^3/s/km^2$ are significantly more frequent in Mack Creek than in Lookout Creek, while the reverse is true for very large peak flows exceeding 2 $m^3/s/km^2$ (Figure 10.7). Some of the apparent differences between the two sites may be due to the much shorter period of record for Mack Creek, which at 19 years is less than half as long as the Lookout Creek record (47 years) and is too short to define the upper end of the frequency curve with much precision. These differences in the shapes of the frequency curves among basins indicate that a logistic regression analysis relating cross section response to flood magnitude will produce somewhat different between-site comparisons depending upon whether Q^* or *RI* is used as the measure of flood magnitude.

10.1.3 Magnitude of the February 1996 Flood

The true magnitude of the maximum instantaneous peak discharge in Lookout Creek on February 7, 1996 is unknown, but is probably within the range of approximately 6,500 to 8,000 cfs (184 to 227 m^3/s), or 2.95 to 3.63 $m^3/s/km^2$, while the recurrence interval might range from 50 to >200 years. The official USGS estimate for the flood

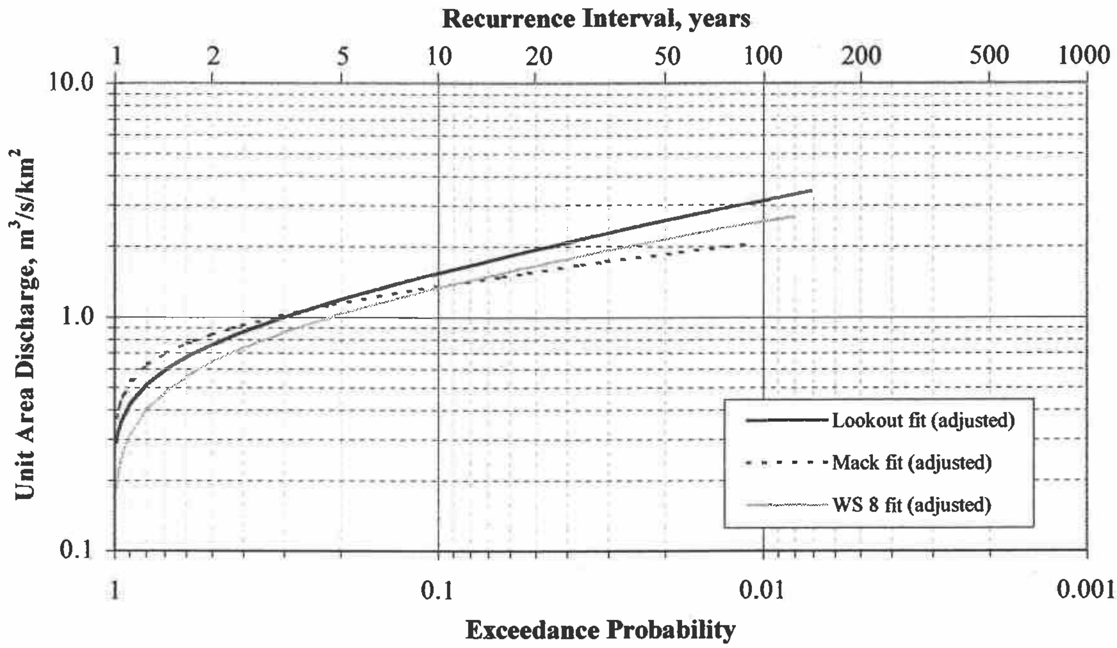


Figure 10.6. Frequency plots for annual maximum instantaneous peak flows in Lookout Creek, Mack Creek, and WS 8, showing fitted Log Pearson Type III curves with expected probability adjustment.

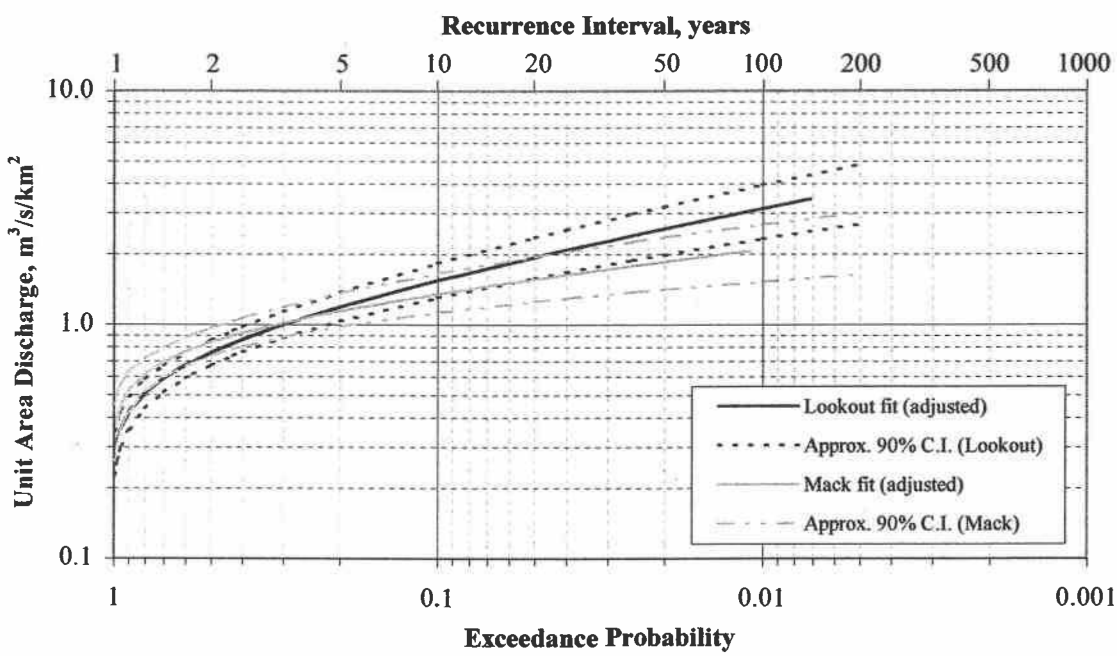


Figure 10.7. Frequency plots for annual maximum instantaneous peak flows in Lookout and Mack Creeks showing fitted Log Pearson Type III curves (with expected probability adjustment) and approximate 90% confidence intervals.

peak is 8,000 cfs (226.5 m^3/s), based on an indirect slope-area calculation using several of the lower Lookout Creek cross sections; this value is considered an estimate only (Herrett, personal communication). Sources of uncertainty in this estimate include:

1. The true channel configuration at the time of the flood peak is unknown. Cross sections at the LOL site, including those used in the slope-area calculation, exhibited large volumes of scour and fill in response to the February 1996 flood.
2. Flow in the reach used for the slope-area calculation was poorly constrained on the right bank, where overbank flows extended onto a forested floodplain surface.
3. The estimated unit area peak discharge of 3.63 $m^3/s/km^2$ is much higher than either the smaller gaged watersheds within the study area (Figure 10.5) or in the neighboring Blue River watershed (2.15 $m^3/s/km^2$, based on a discharge of 8,990 cfs and drainage area of 45.8 mi^2 (USGS, 1999).

What kinds of bounds can reasonably be put on the 8,000 cfs peakflow estimate for Lookout Creek on February 7, 1996? The USGS indirect measurement summary for this estimate acknowledges that "Unit runoff comparison with other sites indicates that the computed discharge seems rather high…but not totally unreasonable. Increasing the n-values 20% would put the unit runoff more in line with other sites at 6,700 cfs." (Herrett, personal communication). For this estimate, both the Manning's *n* and the cross-sectional areas could easily have a 20% or greater error associated with them. Assuming the same unit area discharge as in Blue River, the equivalent peak discharge in Lookout Creek would be only 4,730 cfs, which is clearly too low. A back-of-the-envelope calculation using super-elevation of the high-water surface at the bedrock-controlled bend upstream of XS 8 produces a peakflow discharge estimate of 7,040 cfs (Herrett, personal communication). It is reasonable, therefore, to view the 8,000 cfs estimate as an approximate upper bound for the instantaneous peak discharge in Lookout Creek on February 7, 1996, with the true peak discharge most likely falling within the range of approximately 6,500 to 8,000 cfs.

If the true peak discharge was in fact 6,500 rather than 8,000 cfs, the estimated recurrence interval based on the fitted LP3 flood frequency curve for Lookout Creek (Figure 10.6)—without recalculating the frequency curve—would be approximately 80 years. Alternatively, neglecting the uncertain magnitude of the 1996 flood peak and assuming only that it was in fact the largest flood in 50 years of record (WY 1950-99), the Weibull plotting position estimate (see Section 9.6.2) for the recurrence interval would be 51 years.

It is noteworthy that both the December 1964 and February 1996 floods plot well above the fitted LP3 flood frequency curve for Lookout Creek (Appendix D, Figure D.1). This raises the possibilities that either (1) two very large floods with recurrence intervals of greater than 80 years happened to occur by chance in Lookout Creek within a space of 31 years, or (2) the December 1964 and February 1996 floods are fundamentally different in origin than the other, smaller floods and hence represent a different population of events whose frequency cannot be estimated due to the small sample size (only 2 events).

10.2 Channel Response to 1986 and 1996 Floods

The February 1996 flood produced substantial channel changes at all the cross section sites, but the relative magnitude of response as measured by the mean depth of scour and/or fill at the cross sections was substantially greater at the mainstem Lookout Creek (LOL and LOM) sites than at the tributary (MCC, MAC, and COC) sites. The estimated mean depth of sediments reworked by the flood (i.e., mean depth of scour plus fill) ranged from about 0.15 to 0.2 m at the tributary sites to about 0.5 to 0.6 m at the mainstem Lookout Creek sites (Table 10.2[a]). A total of 62 out of 66 cross sections at all five sites combined, or 94%, exhibited 0.1 m or greater average depth of combined scour and fill (Appendix F). At the Lookout Creek sites, 52% of cross sections experienced ≥ 0.5 m of combined scour and fill, while only one tributary cross section (MCC XS 102) exhibited a change of this magnitude. The Lookout Creek sites exhibited reach scale responses to the February 1996 flood, in which essentially the entire active channel floodway at each site was reworked, nearly

Table 10.2. Summary of average cross section scour and fill at all five study sites in response to the 1986 and 1996 floods: (a) mean depth scour/fill (m); (b) cross-sectional area of scour/fill (m^2).

(a) mean depth of scour/fill (m)

1996

Site	Scour	Fill	Net Δ[1]	Tot. Δ[2]	Tot. Δ/D_{50}[3]
COC	0.09	0.06	- 0.02	0.15	1.58
MAC	0.10	0.10	- 0.00	0.21	2.67
MCC	0.16	0.07	- 0.10	0.23	4.06
LOM	0.13	0.50	+ 0.37	0.63	5.58
LOL	0.27	0.22	- 0.05	0.49	4.94

1986

Site	Scour	Fill	Net Δ[1]	Tot. Δ[2]	Tot. Δ/D_{50}[3]
COC	0.03	0.03	+ 0.00	0.07	0.71
MAC	0.06	0.04	- 0.02	0.11	1.41
MCC	0.04	0.07	+ 0.02	0.11	1.92
LOM	0.08	0.07	- 0.01	0.15	1.30
LOL	0.05	0.11	+ 0.06	0.16	1.63

(b) cross-sectional area of scour/fill (m^2)

1996

Site	Scour	Fill	Net Δ[1]	Tot. Δ[2]
COC	0.55	0.41	- 0.14	0.96
MAC	1.40	1.41	+ 0.01	2.81
MCC	2.31	0.85	- 1.56	3.16
LOM	3.89	14.41	+10.50	18.30
LOL	9.22	6.48	- 2.73	15.70

1986

Site	Scour	Fill	Net Δ[1]	Tot. Δ[2]
COC	0.19	0.16	- 0.04	0.35
MAC	0.91	0.55	- 0.39	1.45
MCC	0.61	0.88	+ 0.28	1.49
LOM	2.40	1.83	- 0.56	4.23
LOL	1.65	3.65	+ 2.01	5.30

(1) Net Δ = Fill - Scour

(2) Tot. Δ = Fill + Scour

(3) D_{50} is the average median particle diameter for all cross sections at a site.

all LWD within the channel was moved, and most riparian vegetation within the active channel floodway was removed or destroyed. Channel response at the tributary sites was more patchy, and disturbance of riparian vegetation was much more limited.

The channel exhibited a substantially smaller response at all cross section sites to the February 1986 flood than to the February 1996 flood, as would be expected given the relative magnitude of these two events. The magnitude of channel response as measured by mean depth of scour and/or fill varied less between sites for the 1986 flood than for the 1996 flood. In particular, the combined depth of scour and fill at the LOL and LOM sites (0.16 and 0.15 m, respectively) was only slightly larger than at the tributary sites in 1986 (0.07 to 0.11 m; Table 10.2[a]). Overall, the cross sections document relatively modest channel response to the flood of February 1986. Only 34 out of 66 cross sections at all five sites combined, or 52%, exhibited 0.1 m or greater combined average depth of scour and fill (Appendix F). These included two cross sections (14%) at the COC site, five (45%) at the MAC site, eleven (58%) at the MCC site, four (78%) at the LOM site, and nine (69%) at the LOL site.

Channel response to the February 1996 and February 1986 floods at each of the cross sections sites are described in greater detail in Sections 10.2.1 through 10.2.4.

10.2.1 Cold Creek Site

In 1996, 12 of 13 cross sections for which change could be quantified at the COC site experienced significant change, with scour dominating in most of the upstream part of the reach and deposition dominating downstream (Figure 10.8[a]), but no discernible disturbance of the riparian zone. These 12 cross sections exhibited either scour or fill (or in one case—XS 3—both scour and fill) of 0.5 m^2 or more, which is roughly the lower limit of reliable change detection using the cross section data. In Cold Creek, where the average channel width is approximately 5.3 m (Table 9.1), 0.5 m^2 represents a significant fraction of the channel cross sectional area. Most of the deposition

Figure 10.8. Longitudinal plots of estimated cross-sectional area of scour and fill between 1995 and 1996 cross section surveys at (a) Cold Creek, (b) Mack Creek old-growth, (c) Mack Creek clearcut, (d) middle Lookout Creek, and (e) lower Lookout Creek sites. Downstream is toward the left in all cases, but longitudinal distance is not to scale. Note that vertical scales are different, but scale is the same at the two Mack Creek sites (b and c) and the two Lookout Creek sites (d and e).

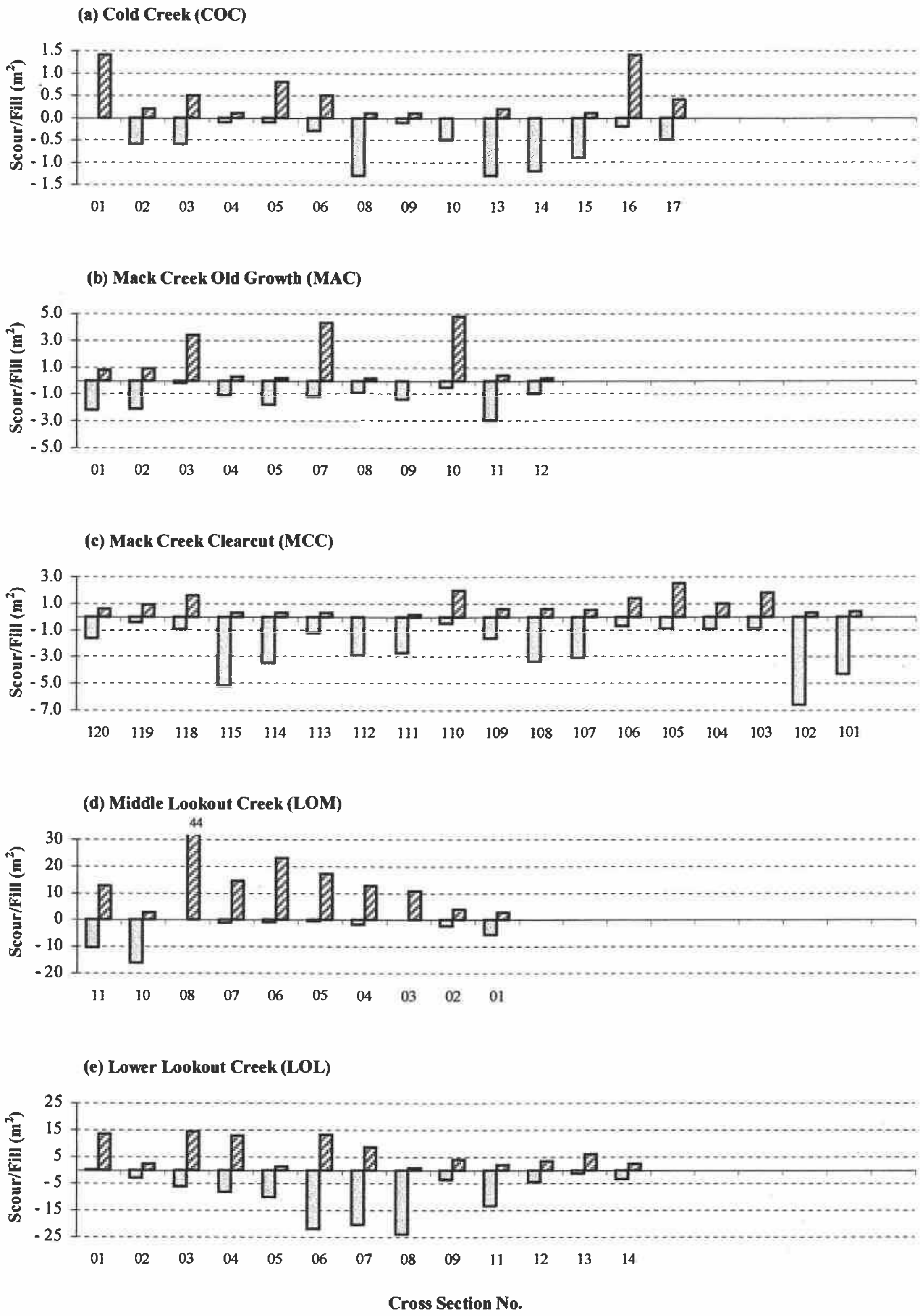


Figure 10.8. (continued)

occurred within the lower half of the reach (XS 1 to 6) or the very upper end of the reach (XS 16 and 17), while scour was the predominant response within the mid to upper part of the reach (XS 8 to 15). Eight cross sections exhibited ≥0.5 m^2 of scour, of which five (XS 8, 10, and 13 to 15) showed *net* scour of ≥0.5 m^2. Five cross sections exhibited deposition of 0.5 m^2 or greater, of which three (XS 1, 5, and 16) exhibited net fill of 0.5 m^2 or greater. Three cross sections (XS 3, 6, and 17) exhibited roughly similar magnitudes of scour and fill. The average net cross section change for the site is -0.14 m^2 (Table 10.2[b]), suggesting very minor net scour at the reach scale.

There was little evidence of significant bank erosion or vegetation disturbance at the Cold Creek site following the flood, even on low surfaces (0.25 to 0.5 m above the summer low-flow water surface) within or adjacent to the channel. Data from meteorological stations in the Andrews Forest suggest it is likely that the banks were covered with a thick blanket of snow at the time of the flood peak. At the end of February 7 (the date of the flood peak), there was 297 mm snow water equivalent (SWE) at the Vanillia Leaf station (elevation 1273 m) and 729 mm SWE at the Upper Lookout station (elevation 1294 m) (Dyrness et al., 1996).

In contrast, cross section data revealed only very minor, patchy scour and fill at the Cold Creek site in response to the February 1986 flood. Only two cross sections exhibited scour (XS 1) or deposition (XS 3) of 0.5 m^2 or greater (Figure 10.9[a]). Scour at four cross sections (XS 1, 2, 8 and 10) exceeded 0.25 m^2 (the approximate lower limit of change detection for the cross section data under ideal conditions), while deposition at four other cross sections (XS 3, 9, 16 and 17) exceeded this amount. Average channel scour and fill amounts at the cross section locations were nearly balanced at 0.19 and 0.16 m^2, respectively (Table 10.2[b]).

10.2.2 Mack Creek Old-Growth and Clearcut Sites

In 1996, the Mack Creek old-growth (MAC) site experienced patchy scour and deposition, but the riparian zone experienced little disturbance (Figure 10.8[b]). Three widely spaced cross sections (XS 3, 7, and 10)—each of which is located just

Figure 10.9. Longitudinal plots of estimated cross-sectional area of scour and fill between 1985 and 1986 cross section surveys at (a) Cold Creek, (b) Mack Creek old-growth, (c) Mack Creek clearcut, (d) middle Lookout Creek, and (e) lower Lookout Creek sites. Downstream is toward the left in all cases, but longitudinal distance is not to scale. Vertical scales on each plot are one-half the scale of the corresponding plot in Figure 10.8, and as in that figure the scale is the same at the two Mack Creek sites (b and c) and the two Lookout Creek sites (d and e).

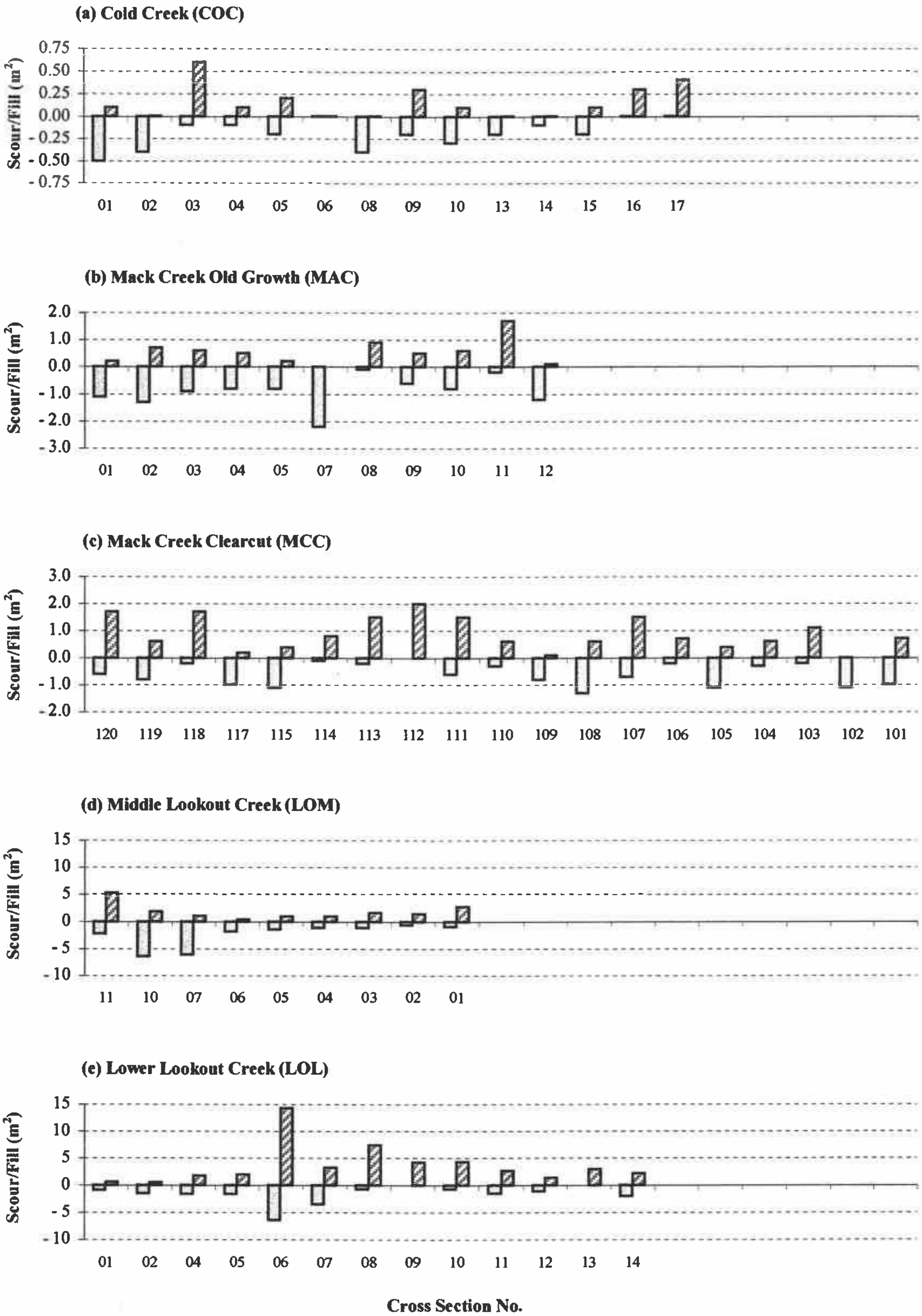


Figure 10.9. (continued)

upstream of an LWD structure (see Section 4.2.1)—exhibited 3 to 5 m^2 of deposition (both absolute and net), which is quite substantial for a channel averaging 13 m in width. Cross section 7 also showed ≥1 m^2 of scour, as did all the remaining cross sections except XS 8. Five cross sections (XS 1, 2, 5, 9, and 11) experienced between 1.2 and 2.6 m^2 of net scour, while the remaining three (XS 4, 8, and 12) exhibited only minor net scour (<1 m^2). The average net change was 0.01 m^2 (Table 10.2[b]), suggesting that this reach as a whole did not experience significant net scour or fill.

The MCC site exhibited a more uniform response in 1996, with substantial net scour being the dominant response (Figure 10.8[c]). Of 18 cross sections for which 1995-96 changes could be quantified, 13 (72%) exhibited scour of ≥1 m^2, and 10 exhibited >1 m^2 of net scour. The greatest amount of scour occurred at XS 101 and 102 (at the upstream end of the reach) and XS 114 and 115, all of which showed evidence of between approximately 3 and 6 m^2 of scour. However, the response of XS 101 and 102 was probably significantly influenced by the presence of a 2+ m high waterfall at the gaging station flume just a few meters upstream. Six cross sections exhibited ≥1 m^2 of fill, but only two of these (XS 105 and 110) exhibited >1m^2 of net deposition. For the reach as a whole, the average net change was -1.6 m^2 (Table 10.2[b]), indicating significant net scour.

This scour was accompanied by a pronounced coarsening of the bed surface. Particle size data provide convincing evidence (p-values ≤ ~0.01 from a paired t-test) of an increase in all particle size fractions at the MCC site, with the most pronounced changes at the coarse end of the particle size distribution (Table 10.3). The D_{84} increased from an estimated 224 mm in 1995 to 396 mm in 1996 (a 77% increase), while the D_{50} increased from an estimated 60.9 to 95 mm (56%), and the D_{16} increased from 14.5 to 20.4 mm (41%).

The overall pattern of channel response to the 1996 flood in the clearcut reach was substantial scour alternating with relative minor deposition, with a greater "patch size" of contiguous channel exhibiting similar channel response than in the old-growth reach. Downstream of the uppermost two cross sections, XS 103 to 106 showed relatively minor net deposition (1.6 m^2 maximum) to no significant change (Figure 10.8[c]). The next three cross sections exhibited minor to moderate net scour (1 to

Table 10.3. Selected 1995 and 1996 particle size statistics for the cross section sites. Indicated p-values for between-year comparisons are from a paired t-test, using log-transormed data, of the hypothesis that the mean difference between 1995 and 1996 values is zero, with the alternative hypothesis that the difference is nonzero; values of 0.05 or less are shown in boldface. The p-values in the bottom row of the table are from a two-sample t-test, also using log-transformed data, for a difference between sites in a given year.

			D_{84}		D_{50}		D_{16}	
Site	Parameter	n	1996	1995	1996	1995	1996	1995
LOL	mean	13	224	226	90.5	99.4	12.3	31.0
	95% C.I.		187-268	202-252	71.5-115	84.0-117	6.4-23.7	22.8-42.1
	p-value		0.9282		0.4909		**0.0044**	
LOM	mean	10	236	309	86.9	149.0	18.4	39.0
	95% C.I.		188-295	281-340	71.4-106	130-171	10.0-33.8	21.8-69.5
	p-value		**0.0436**		**0.0002**		0.0774	
MCC	mean	17	396	224	95.0	60.9	20.4	14.5
	95% C.I.		363-432	186-269	83.2-108	49.7-74.7	17.3-24.0	12.2-17.2
	p-value		**<0.0001**		**0.0026**		0.0136	
MAC	mean	11	273	280	68.9	80.9	19.1	19.3
	95% C.I.		179-414	198-394	48.2-98.6	57.4-114	14.3-25.5	14.2-26.4
	p-value		0.8821		0.3136		0.9163	
COC	mean	3	319	263	93.5	92.1	19.5	29.2
	95% C.I.		152-667	185-375	90.3-96.8	38.9-205	13.8-27.4	16.6-51.5
	p-value		0.4501		0.9480		**0.0381**	

2.8 m^2), followed by modest net fill (1.5 m^2) at XS 110. Cross sections 111 to 115 showed generally quite substantial net scour (approximately 3 to 5 m^2, except at XS 113). At the downstream end of the reach, XS 118 and 119 showed no significant net change, while XS 120 exhibited 1 m^2 of net scour.

The cross section profiles (Appendix B) provide no evidence of significant bank erosion at the old-growth or clearcut sites resulting from the February 1996 flood, although evidence of localized bank erosion (e.g., exposed roots and scoured surfaces on the bank) was observed following the flood. In the clearcut reach, a few alders were undercut and toppled, and the willow growing on either side of the main channel was somewhat battered and undoubtedly pruned back by the flood, but in general the riparian vegetation within and adjacent to the channel was not heavily disturbed in either reach (Figures 4.3 and 9.4).

In contrast, in 1986 the old-growth site experienced moderate scour throughout its length, but the clearcut site experienced both deposition and scour. Channel response to the February 1986 flood at the MAC cross sections was moderate but ubiquitous. All 11 cross sections exhibited scour and/or fill exceeding 0.5 m^2 (Figure 10.9[b]). Scour exceeded deposition at all but two cross sections (XS 8 and 11), with four (XS 1, 2, 7, and 12) showing >1 m^2 of scour while only XS 11 showed >1 m^2 of fill. The largest response observed was 2.2 m^2 of scour at XS 7, which was likely the result of release of relatively fine sediment (predominantly gravel) stored upstream of the LWD jam just downstream of this location. Average scour and fill amounts were 0.9 and 0.6 m^2, respectively (Table 10.2[b]), suggesting that minor net scour occurred within the reach.

In the Mack Creek clearcut reach just downstream, all 19 cross sections also exhibited detectable change, but deposition predominated over scour, with 11 sections exhibiting net deposition to 8 showing net scour (Figure 10.9[c]). Seven cross sections had >1 m^2 of deposition, while 6 had >1 m^2 of scour. The cross sections show a longitudinal pattern of alternating scour and fill, with the patches of net deposition punctuated by shorter intervals net scour. The average scour and fill amounts for the cross sections at the clearcut site were 0.6 and 0.9 m^2, respectively

(Table 10.2[b]), suggesting that minor net deposition occurred within the reach that was similar in magnitude to the net scour at the old-growth site for this event.

10.2.3 Middle Lookout Creek Site

In 1996, the LOM site experienced substantial and extensive channel aggradation upstream of a LWD jam, significant fining of the bed, reactivation of side channels, a large lateral channel shift, and significant bank erosion. A major sediment pulse was deposited upstream of a newly formed channel-spanning LWD jam (built on a pre-existing jam that only partially spanned the channel) in the vicinity of XS 9 (Figure 9.6, location C), resulting in substantial aggradation of the channel extending at least 170 m upstream to XS 2 (Figure 10.8[d]), where approximately 0.5 m of sediment was deposited within the channel thalweg (Appendix B). Up to two meters of deposition is estimated to have occurred in the channel thalweg (approximately 1.2 m averaged over the entire channel width) at XS 8 and 9 just upstream of the obstruction (Appendix B), where in excess of 40 m^2 of net fill is suggested by the cross section data. (The precise amount is somewhat uncertain due to erosion of the south bank and loss of the cross section posts there in 1996.) The amount of deposition within the channel decreases nearly monotonically upstream (Figure 10.8[d]), suggesting that it represents a large wedge of sediment that can be thought of as a single depositional feature unlike the isolated, localized deposition documented at the Cold Creek and Mack Creek sites.

This aggradation was accompanied by significant fining of the bed surface. Median particle diameter decreased from an estimated 149 mm in 1995 to 86.9 mm in 1996, a 42% decrease (p-value of 0.0002, Table 10.3). The D_{84} and D_{16} size fractions also decreased, from 309 to 236 mm (-24%) and 39 to 18.4 mm (-53%), respectively, although the evidence of change is less conclusive (p-values of 0.04 and 0.08, respectively).

The form of the channel at the LOM site in plan view (Figure 9.6) reflects its aggradational nature and illustrates the interaction between LWD and sediment. Large alternate bars, whose tops in some cases are close to the height of the adjacent conifer forested floodplain (Figure 9.7), are a prominent feature of the reach. Several of these are stabilized by or deposited against LWD (e.g., Figure 9.6, locations A and B). Between XS 4 and 5, two large, old conifer logs were deposited, jointly spanning the entire channel on a diagonal from the north bank at XS 4 to the south bank at XS 5. One log, deposited on a lateral bar along the north bank, anchors a sediment accumulation on its upstream side, which is about 0.75 m higher than the bar downstream of the log (Figure 9.6, location A). The second log, suspended above the low-flow channel, anchors a marginal accumulation of LWD along the south bank at its downstream end (Figure 9.6, location F). At XS 1, a small LWD accumulation deposited by the 1996 flood on the north bank also anchors an upstream bar and stabilizes a downstream bar by deflecting current toward the opposite bank (Figure 9.6, location B).

Immediately downstream of the LWD jam at XS 10, two thalwegs present in 1995 were partially filled and the bar separating them was scoured to a depth of approximately 1 m, creating a single new thalweg (Appendix B). Relatively minor net channel scour of approximately 2.3 m^2 within the channel bed was accompanied by an estimated 4 m of bank erosion on the south (left) bank, accounting for the bulk of the apparent "scour" at this section in Figure 10.8(d). The amount of bank erosion and quantities of scour and deposition are uncertain at this location due to loss of the cross section post on the south bank during the flood. A small angular error in reestablishing the cross section could account for some of the apparent change, but the significant bank retreat of at least 2 to 3 m is clearly shown by XS 9 and 10 and flood-related slope failures on the south bank in this vicinity (Figure 9.6). Fifty meters farther downstream at XS 11, the channel shifted laterally (Appendix B), producing nearly balanced areas of scour and fill at this cross section (Figure 10.8[d]).

Banks along both sides of the channel show evidence of recent scour in the vicinity of XS 2, where the channel is at its narrowest (Figure 9.6). The profiles for XS 2 (Appendix B) suggest that 2 to 3 m of bank erosion occurred along the south bank at this location as a result of the 1996 flood. Bank erosion also occurred on the south bank at XS 5, where a large channel-spanning log diverted floodwaters against the bank (Figure 9.6, location F).

A network of side channels within the extensive conifer-forested floodplain surfaces on either side of the channel (e.g., locations D, E in Figure 9.6) was active during the 1996 flood. On the north side of Lookout Creek between XS 4 and 7, the floodplain is lower than the low-flow water surface in the main channel. Several side channels branch off in this area, but are blocked or partially blocked by mostly older LWD that probably was deposited by the 1964 flood (Figure 9.6, location D). A side channel entrance at XS 6 apparently was created or reactivated in the 1996 flood when the marginal accumulation of LWD was breached, creating what is now the main active entrance to a 5-m-wide side channel that flows through the forest for several hundred meters before rejoining the main channel downstream of the cross section reach. This side channel had flow up to 2 m or greater in depth during the flood (based on deposits of floated organic matter), which deposited a substantial LWD jam and associated sediment about 150 m downstream of the main entrance at XS 6 (Figure 9.6, location G).

In contrast, in 1986 the LOM site experienced moderate deposition and scour along its length, with some minor amounts of channel shifting and bank erosion. The cross section profiles exhibited modest deposition at the upstream end of the reach, where about 3 m^2 of deposition filled the channel thalweg to a depth of 30 to 40 cm at XS 1 (Appendix B) and somewhat lesser amounts of net deposition occurred at XS 2 and 3 (Figure 10.9[d]). More substantial deposition of 5 m^2, partially offset by scour, occurred at XS 11 at the downstream end of the reach; these changes were the result of a lateral shift of the thalweg accompanied by deposition of a new bar along the left side of the channel and erosion of an existing bar on the right side (Appendix B). Cross sections 6 through 10, located in the vicinity of the LWD jam[3] (Figure 9.6, location C), exhibited 1.4 to 5.1 m^2 of net scour in response to the February 1986 flood. Field notes from the 1986 cross section survey indicate that changes in the vicinity of XS 10 and immediately upstream were associated with the downstream pivoting of the rootwad end of an old-growth cedar log (one of the key logs anchoring

[3] Prior to 1996, this LWD accumulation was limited to the right (north) side of the channel; two or three large logs suspended between the right channel margin and the high left bank (well above the water surface) provided an anchor for the subsequent channel-spanning accumulation of LWD during the 1996 flood.

the LWD jam that formed at XS 9 in 1996), whose other end rests high on the left bank. The pivoted end came to rest against another large log projecting down into the channel from the left bank. This apparently blocked the main channel thalweg, which previously was located adjacent to the right bank, and led to the scouring of a new thalweg to the left of the obstruction.

10.2.4 Lower Lookout Creek Site

In 1996, the LOL site experienced wholesale channel restructuring, including large scale lateral channel shifts, channel scour, aggradation, bank erosion and channel widening, export of LWD, and complete removal of riparian alders from mid-channel and lateral bars. Cross section profile plots for this reach in 1995 and 1996 (Appendix B) show a wide range of channel responses to the flood:

1. lateral shifting of the main channel involving substantial scour and fill at the same cross-section (e.g., XS 3, 6, 7),
2. substantial channel degradation or net scour (XS 5, 8, 10, 11),
3. major aggradation (XS 1),
4. channel widening with or without aggradation (XS 4 and 5, respectively), and
5. relatively minor scour and fill (XS 2, 9, 12, and 14).

The maximum depth of scour was approximately 2 m at XS 6 to 8, while portions of XS 3 and 4 experienced up to 1.5 m of deposition and XS 1 experienced nearly 2 m of aggradation (Appendix B).

In general, the volume of deposited material decreased with distance upstream of the lowermost cross section, while the volume of bed material eroded from the channel was greatest just below the bend (XS 6 to 8) and decreased both up- and downstream from there (Figure 10.8[e]). To the extent that the cross section profiles constitute a representative sample of the channel bed changes in this reach, the cross-section data indicate a greater volume of scour than of deposition, implying that a net export of sediment from the reach occurred during the flood. This is somewhat surprising, given that a large input of sediment (and LWD) occurred approximately one kilometer upstream due to a debris flow in a tributary (WS 3), much of which is likely to have entered the study reach due to the limited sediment storage capacity of the channel in the intervening bedrock gorge. However, a large, new cobble-and-gravel bar on the right (west) side of the channel just downstream of the bedrock outcrop below XS 1 (the very upper end of which is shown at the bottom of Figure 9.8[b]) suggests that the deposition at XS 1 may represent just the upstream end of a much larger depositional feature.

The fine size fraction of the bed became significantly finer at the LOL site in 1996. While there was no evidence of change in the D_{50} or D_{84} particle size fractions, there was strong evidence (p-value of 0.004) for a decrease in the finer particle size fractions represented by the D_{16}, which decreased by 60%, from an estimated 31 mm in 1995 to 12.3 mm in 1996. This suggests that the proportion of fine sediment (sand and fine gravel) exposed on the bed at the LOL site increased between 1995 and 1996.

The most prominent channel change occurred downstream of a bedrock constrained bend at XS 9 (Figure 9.8), where the stream abandoned its main low-flow channel on the west side of the active channel floodway (Figure 10.10) after its upstream end was blocked by deposition of a large plug of coarse sediment (boulders and large cobbles). Presumably prior to the channel switch, the flood scoured away about 1 to 1.5 m of the west bank in the vicinity of XS 6 and 7. Subsequently (perhaps contemporaneously with the switch), the flood cut a new main channel along the high terrace forming the east bank, where a side channel was previously located (Figure 10.11), by scouring up to 2 m of sediment in the vicinity of XS 6 to 8 (Appendix B). Video footage recorded during the flood (Grant and Swanson, 1996) documents that these changes occurred before 8:30 a.m., or more than 2½ hours before the flood peak at 11:00 a.m (Henshaw, personal communication).

At the same time (i.e., before 8:30 a.m.), the flood removed several old-growth logs and a stand of riparian alder that had occupied a large mid-channel bar at this location (Figures 9.8 [location B], 10.10, 10.11). Prior to the flood, this bar was vegetated with 15 to 20-cm diameter alders (Figure 10.11[a]), and the channel divided around the bar, with the main flow going west of the bar and several small channels cutting across the bar (Figure 9.8[a]). The 1996 flood stripped off the alder forest on

(a)

(b)

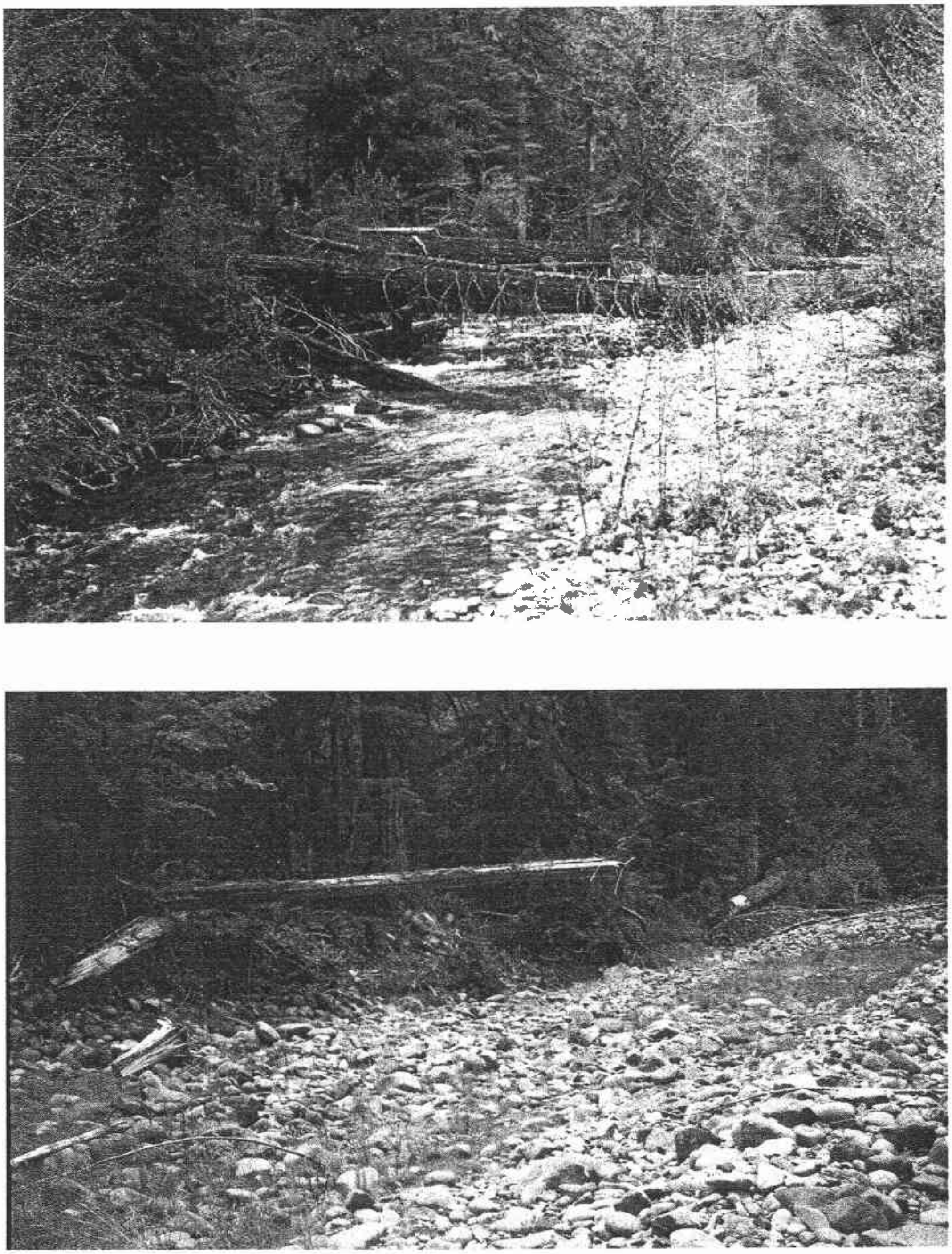


Figure 10.10. Two views along the west bank of Lookout Creek at the LOL site showing channel change due to the February 1996 flood: (a) 1986, view upstream from XS 6; (b) 1997, view of same area from a bit farther downstream, looking more toward west. Downstream-pointing log visible at right in (b) is part of one of the channel-spanning logs visible in (a), which was broken off and pivoted downstream by the February 1996 flood. (1986 photo courtesy of Forest Science Data Bank)

(a)

(b)

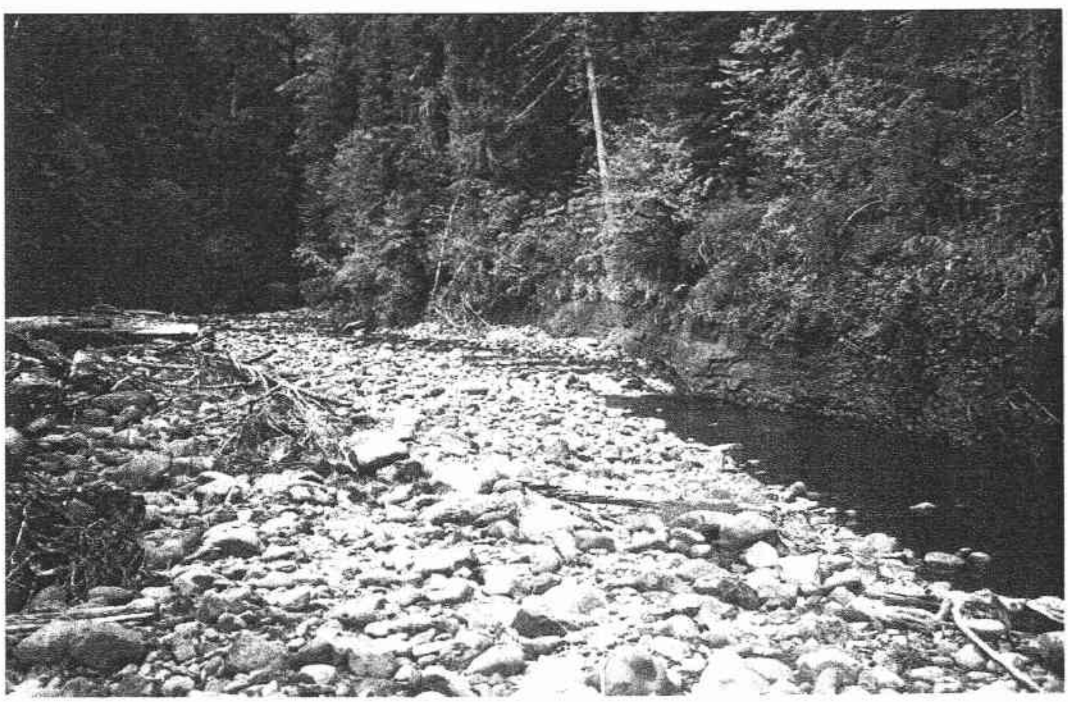


Figure 10.11. View upstream along east bank of LOL site: (a) end of spanner logs between XS 7 and XS 8 in 1986 (same logs as in Figure 10.10 [a]); (b) same area viewed from slightly farther downstream in 1997. Channel was incised by 1.5 to 2 m on east bank during the February 1996 flood; note position of vegetation line in (a) and (b) above. (1986 photo courtesy of Forest Science Data Bank)

the bar, leaving a few prone, dead alders still rooted in place, and eliminated all the very large old-growth logs and most of the in-channel LWD from the reach. However, the bar remained and grew in length (both up- and downstream) and in width (through lateral accretion on the west side).

While not well documented by the cross sections, erosion of the high terrace forming the left (east) bank of this reach is clearly indicated by undercut and toppled alders and an undercut old-growth Douglas-fir tree with half its rootwad overhanging the channel in the vicinity of XS 8 A crescent shaped alcove in the bank extending 8 to 10 m downstream from XS 6 containing a pocket of large boulders clearly derived from the adjacent alluvial fan debris flow deposits, and exposed roots and small failures in the overlying fluvial terrace deposits long this bank between XS 4 and 9 (Figure 9.8) also suggest at least patchy erosion of the west bank.

Downstream of the large central bar, approximately 6 m of bank retreat occurred at XS 4 and 10 m at XS 5 occurred along the right bank. In this area, an approximately 6- to 12-m wide patch of floodplain forested with alders and maples—including some mature bigleaf maples—was removed during the 1996 flood, presumably after a large downstream pointing log with rootwad which had protected this area (Figure 9.8) was mobilized by the flood waters. The flood video (Grant and Swanson, 1996) indicates that these changes and those downstream occurred sometime after 9:00 a.m. (i.e., subsequent to the switching of the main channel from the west to the east side of the central bar downstream of the bedrock bend), but the timing relative to the flood peak is not known.

Downstream of XS 5, the pre-1996 channel was simpler than it was upstream of this point, with a single, straight thalweg along the east side of the active channel between XS 5 and 3 that switched to the left side of the channel downstream of this point (Figure 9.8[a]). Alternate bars occupied the side of the channel opposite the thalweg within this reach. During the 1996 flood, the channel thalweg and bars essentially switched places, such that the current channel configuration is essentially 180° out-of-phase with the pre-flood configuration (Figure 9.8).

In contrast with the 1996 flood, deposition was the dominant response to the February 1986 flood at the LOL site. The average amount of deposition indicated by the cross sections in 1986 (3.65 m^2) was more than double the average amount of scour (1.65 m^2, Table 10.2[b]). Both scour and deposition were greatest in the vicinity of XS 6 to 8 (Figure 10.9[e]), where several old-growth logs fell into the channel from the right (west) bank during the winter of 1981-82 due to windthrow and bank erosion (Figure 9.8[a]; Nakamura and Swanson, 1993). Substantial deposition also occurred along the inside of the sharp bedrock-constrained bend just upstream (XS 9 to 11, Figure 9.8), where the cross sections document lateral and vertical accretion of the point bar on the inside of the bend (Appendix B). Significant net deposition (2.9 m^2) also occurred at XS 13, near the upstream end of the LOL site. Only relatively minor deposition and scour occurred in the upstream and downstream ends of the reach (Figure 10.9[e]).

10.2.5 Changes in Channel Morphology at the Lower Lookout Creek Site Over Two Decades

The historical changes in the LOL reach from 1977 to the present illustrate how the input of LWD, the growth of riparian vegetation, and the interaction of these processes with peak flows and sediment can lead to the development of channel complexity. In 1977, there was little sizable woody debris within the channel, although there were some marginal accumulations of relatively short pieces of LWD (<10–15 m in length)—probably a legacy of the December 1964 flood—on the right bank in the vicinity of XS 6 and between XS 7 and 8. The summer low-flow channel downstream of the bedrock-constrained bend hugged the right (west) bank (Figure 10.12[a]). A high-water channel split off about 15 m upstream of XS 8 and ran along the edge of the terrace forming the left bank before rejoining the main channel at XS 6. A large mid-channel bar separated the high-water side channel from the main channel. Within the bedrock bend, a riffle split around a small mid-channel bar at low-flow. By 1984 (Figure 10.12[b]), four large old-growth trees had fallen into the channel from the right bank as a result of windthrow and bank erosion in the vicinity

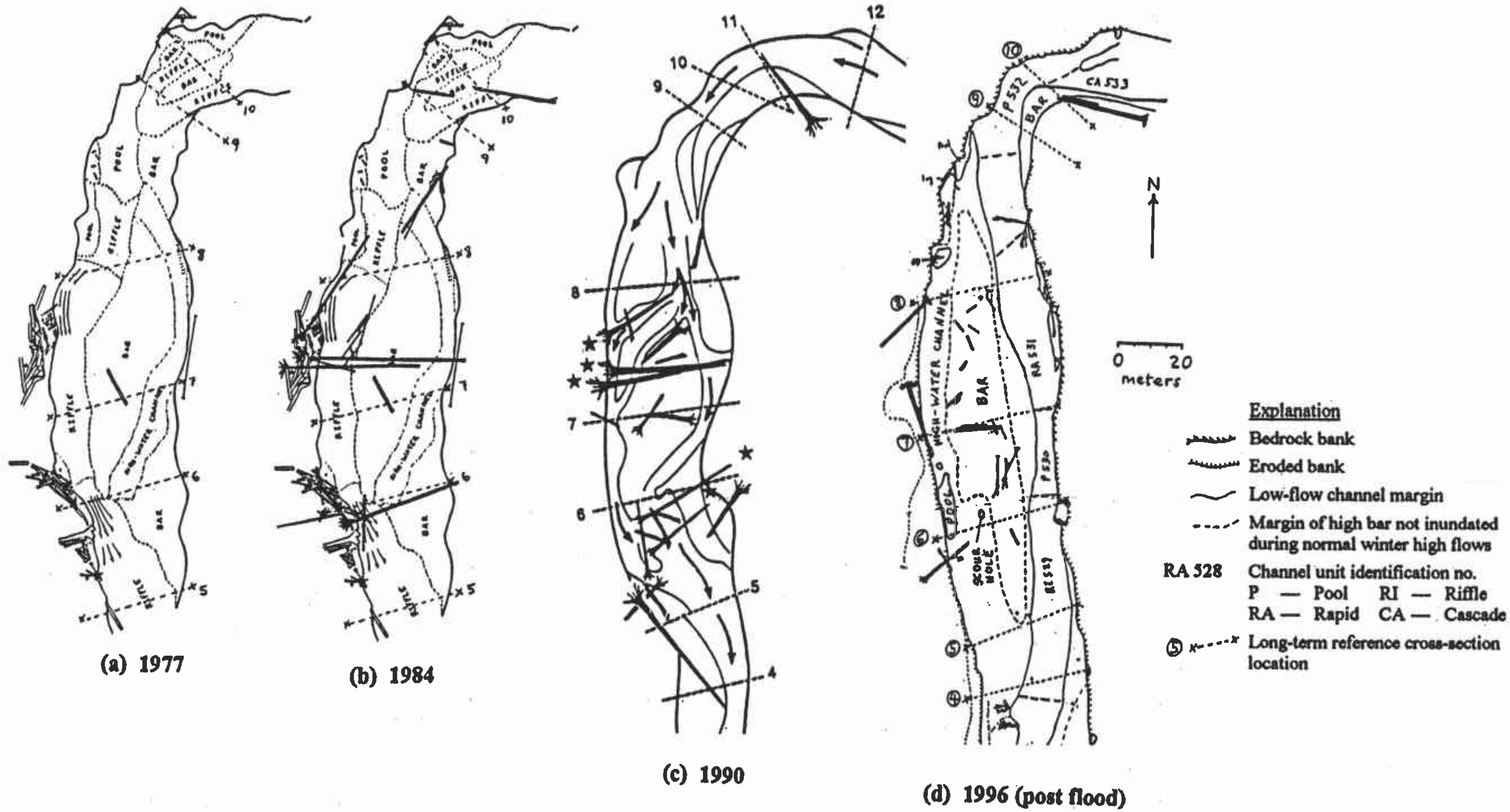


Figure 10.12. Channel changes in a portion of the lower Lookout Creek (LOL) site, 1977-1996. LWD emplaced after 1977 is shown in black (solid) on the 1984 map using the 1977 base (i.e., changes in the channel configuration were not mapped, but are believed to have been minor). Sources: (a) and (b) are modified from unpublished data by G. Lienkaemper; (c) is from Nakamura and Swanson (1993); (d) is by the author.

of XS 6 to 8 during the winter of 1981-82[4] (Nakamura and Swanson, 1993), and additional smaller logs had fallen or floated into this portion of the channel. A 25+ m long log had floated or fallen in along the left bank at the inside of the bedrock bend, projecting out into the channel in the bend. By 1990 (Figure 10.12[c]), additional logs had accumulated in the channel and the channel morphology had become increasingly complex, with multiple threads flowing on either side of and crossing the alder-covered bar between XS 6 and 8. A new downstream-pointing log projecting into the channel from the right bank upstream of XS 5 anchored upstream and downstream bars. The log on the inside of the bedrock constrained bend had apparently been replaced by a larger log projecting most of the way across the channel immediately upstream of XS 11 by 1990, and growth of a point bar on the inside of the bend had narrowed the channel and forced it against the bedrock wall on the right bank.

Most of the changes evident between 1984 and 1990 in Figure 10.12 probably occurred in connection with the flood of February 1986. Historical photographs help to document the channel and riparian vegetation response to the February 1986 and February 1996 floods in this reach. Figures 10.13 (a) and (b) show a view looking upstream from the large channel-spanning log at XS 6 toward the channel-spanning logs upstream of XS 7 in 1985 and 1986, respectively. These photos reveal modest changes at this location: the channel thalweg in the foreground appears to have deepened; exposed, undercut roots provide evidence of bank scour; two smaller new logs have floated in beneath the spanner logs; and vegetation on the bar appears to have been pruned by the flood. Figure 10.11(a) is an upstream view along the opposite bank of the far end of the spanner logs in Figure 10.13 in the summer of 1986. This photo shows the dense stand of alder that had become established on the large central bar by this time, apparently undisturbed to any significant extent by the February 1986 flood. The February 1996 flood completely removed this alder stand as well as the spanner logs, and incised the channel at this location by 1.5 to 2 m while widening it as well (Figure 10.11[b]).

[4] Survey data for XS 6 suggest that 3-4 m of bank retreat may have occurred at this location between 1981 and 1982.

(a)

(b)

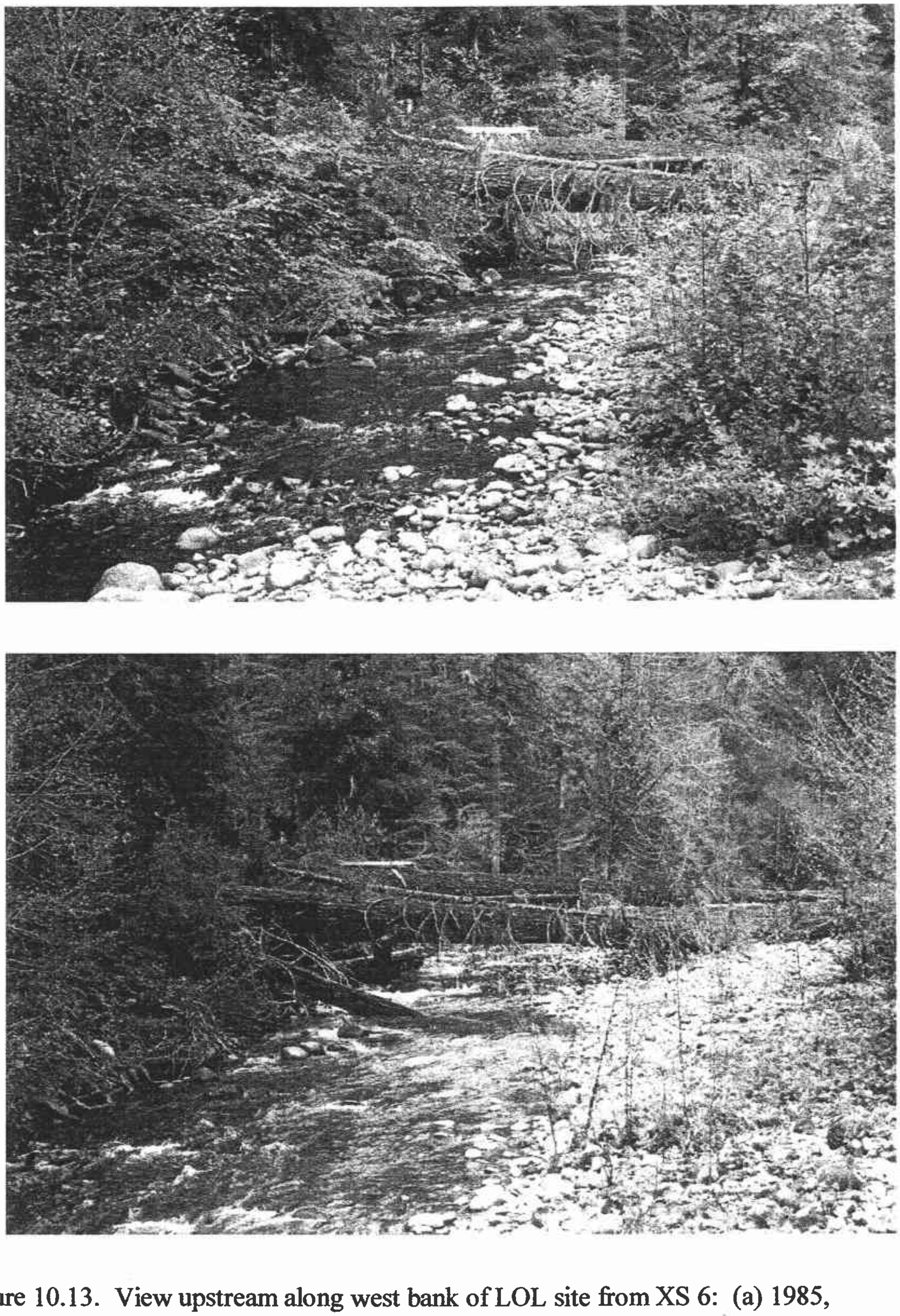


Figure 10.13. View upstream along west bank of LOL site from XS 6: (a) 1985, (b) 1986. Modest channel changes ascribed to the February 1986 flood include bank and channel scour (note the exposed roots and apparently deeper thalweg in the left foreground of [b]), input of new logs beneath large spanner logs, and reduced vegetation on bar at right. (Photos courtesy of Forest Science Data Bank)

As previously described, the flood of February 1996 essentially completely reset the channel, resulting in a straightened, simplified channel morphology (compare Figures 10.12 [c] and [d]). The flood removed most of the LWD from the channel, including all of the channel-spanning logs. The log on the inside of the bedrock bend remained, but was pivoted downstream against the bank, and the point bar built up higher. The channel along the right bank was blocked by a deposit of boulders and large cobbles just downstream of the bend, and the stream cut a new, deeper, straighter channel along the edge of the high terrace on the left bank.

10.3 Magnitude of Cross Section Response in Relation to Peak Flow Magnitude

Channel cross section responses were similar among sites over time, and relatively little channel response was recorded by the cross sections during most years between 1978 and 1998 (Figure 10.14). Response index scores rarely exceeded a value of 0.2, and only 1996 (all sites), 1986 (all sites except MCC), and 1997 (both Lookout Creek sites) produced responses exceeding a value of 0.4. Cross section response index scores at the two Lookout Creek sites were remarkably similar after 1985, but the LOL site exhibited greater change than the LOM site prior to 1985 (Figure 10.14). One reason for this may be relatively large changes at LOL XS 6 to 8 following the introduction of several old-growth conifer logs into the channel in their vicinity in the winter of 1981-82; these cross sections are responsible for a disproportionate share of the response index score at the LOL site during these years (Appendix B). Response index scores for the Mack Creek sites track each other less closely than do those for the Lookout Creek sites, but are still generally very similar.

Flood magnitude, Q^*, and the cross section response index show a definite linear relationship at all sites (Figure 10.15). The response index shows a stronger relationship to discharge at the Lookout Creek sites than the Mack Creek sites, accounting for 74% and 70% of the variance in the response index scores for the LOL and LOM sites, respectively, vs. 59% and 54%, respectively, for the MCC and MAC sites. (The 1996 response index scores have been excluded from the regression fit for all sites.) Response index scores for the Mack Creek sites for the 1996 flood are

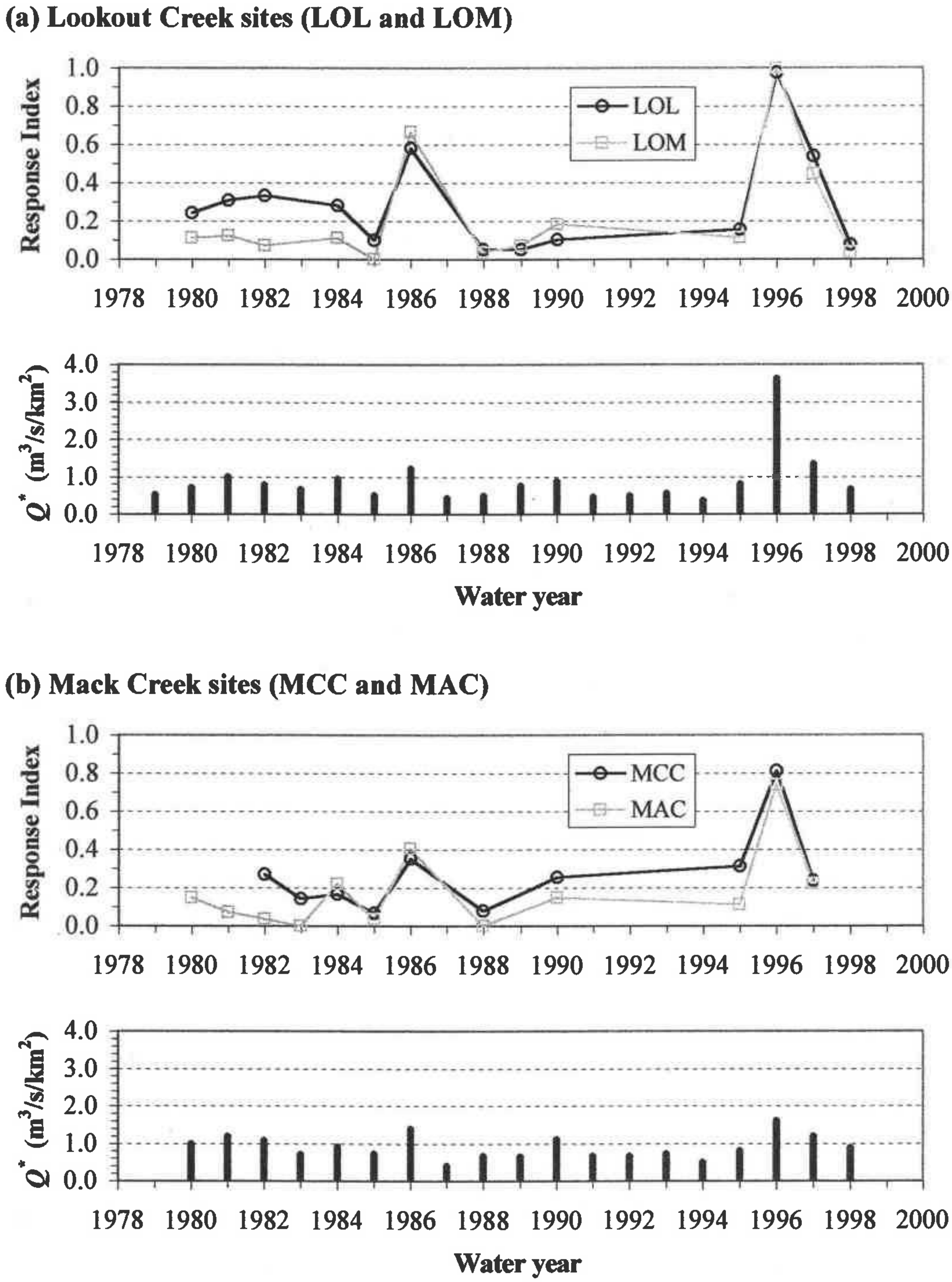
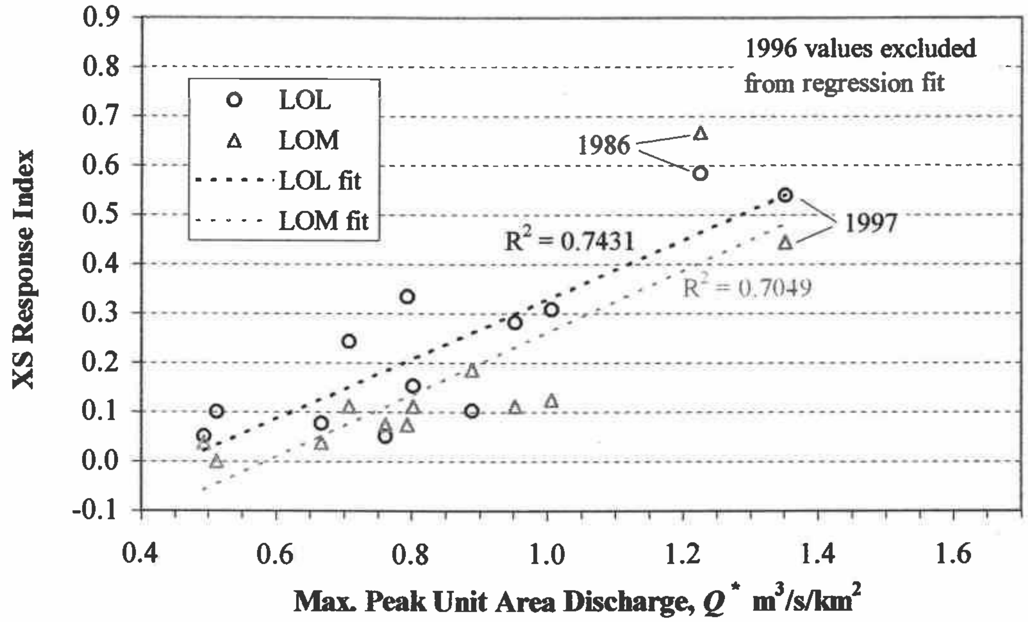


Figure 10.14. Cross section response index scores and maximum instantaneous peak unit area discharge (Q^*) for (a) Lookout Creek sites (LOL and LOM), and (b) Mack Creek sites (MCC and MAC).

(a) Lookout Creek sites



(b) Mack Creek sites

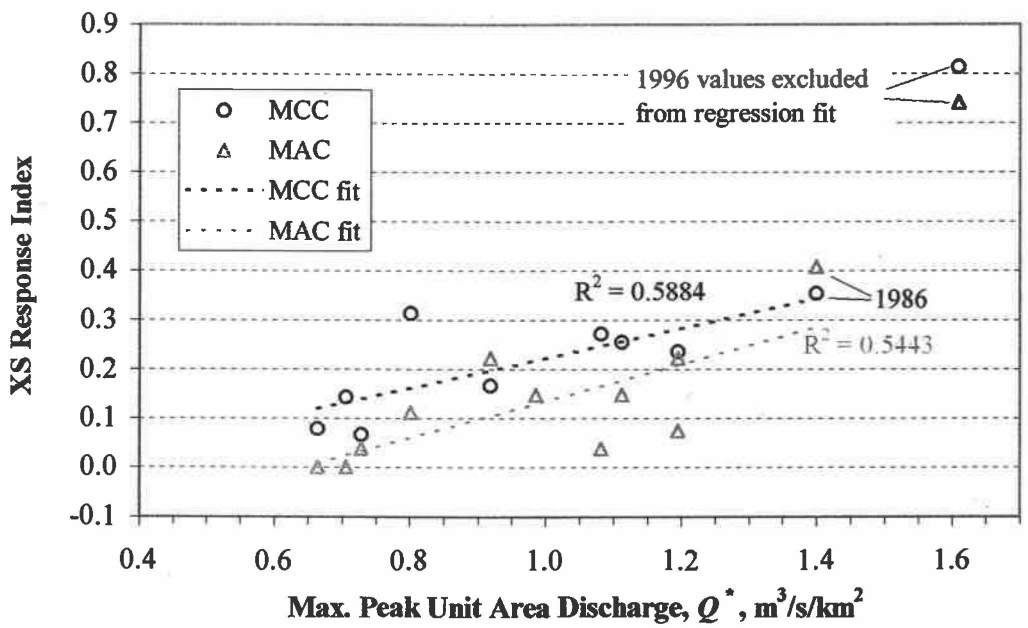


Figure 10.15. Scatter plots of cross section response index scores vs. maximum peak unit area discharge, Q^*, for (a) Lookout Creek sites, and (b) Mack Creek sites. The 1996 flood has been omitted from the Lookout Creek plots so that these can be shown at the same scale as the Mack Creek plots.

approximately twice as great as the response that would be predicted by the simple linear regression of response index vs. Q^*. They are also approximately twice as great as the response index scores for the 1986 flood, despite only a 14% difference in Q^* between the 1986 and 1996 floods. These results provide some evidence for a threshold-like response at the Mack Creek sites for peak flows significantly exceeding the 1986 discharge of 1.4 $m^3/s/km^2$.

Residuals from the regressions of the cross section response index vs. Q^* shown in Figure 10.15, when plotted vs. water year, indicate that the relationship between cross section response and Q^* is not time-dependent, and that it is reasonable to analyze the cross section changes in relation to Q^* without considering the historical sequence of floods (Figure 9.19). None of the residual plots shows a trend through time or an abrupt shift. The large positive residuals in the Mack Creek plots for the 1996 flood (Figure 9.19[b]) reflect the possible threshold-like response at the Mack Creek sites discussed above, while the large negative residual for the Lookout Creek sites (Figure 9.19[a]) simply reflects the inability of the response index to characterize channel response to very large events.

10.4 Probability of Cross Section Change in Relation to Magnitude and Frequency of Peak Flow Events

Despite considerable scatter in the observed values in a plot of cross section response proportion p vs. Q^*, the fitted logistic regression models explain the general pattern of variation in the cross section responses within and between sites (Figures 10.16, 10.17). Fitted slope and intercept parameters for each site all had p-values well below 0.01 (Appendix G, Table G.1). The fitted Q^* response curves for the LOL, LOM, and MAC sites are very similar in shape (LOL and MAC are nearly identical), but the MAC curve is offset to the right of the two Lookout Creek curves, while the MCC curve has a lower slope (Figure 10.16). The offset of the MAC curve indicates that a higher unit area discharge is associated with any given response probability p at the Mack Creek old-growth site vs. the Lookout Creek sites. The LOM curve is nearly coincident with the LOL curve for response probabilities above about 0.6 (or,

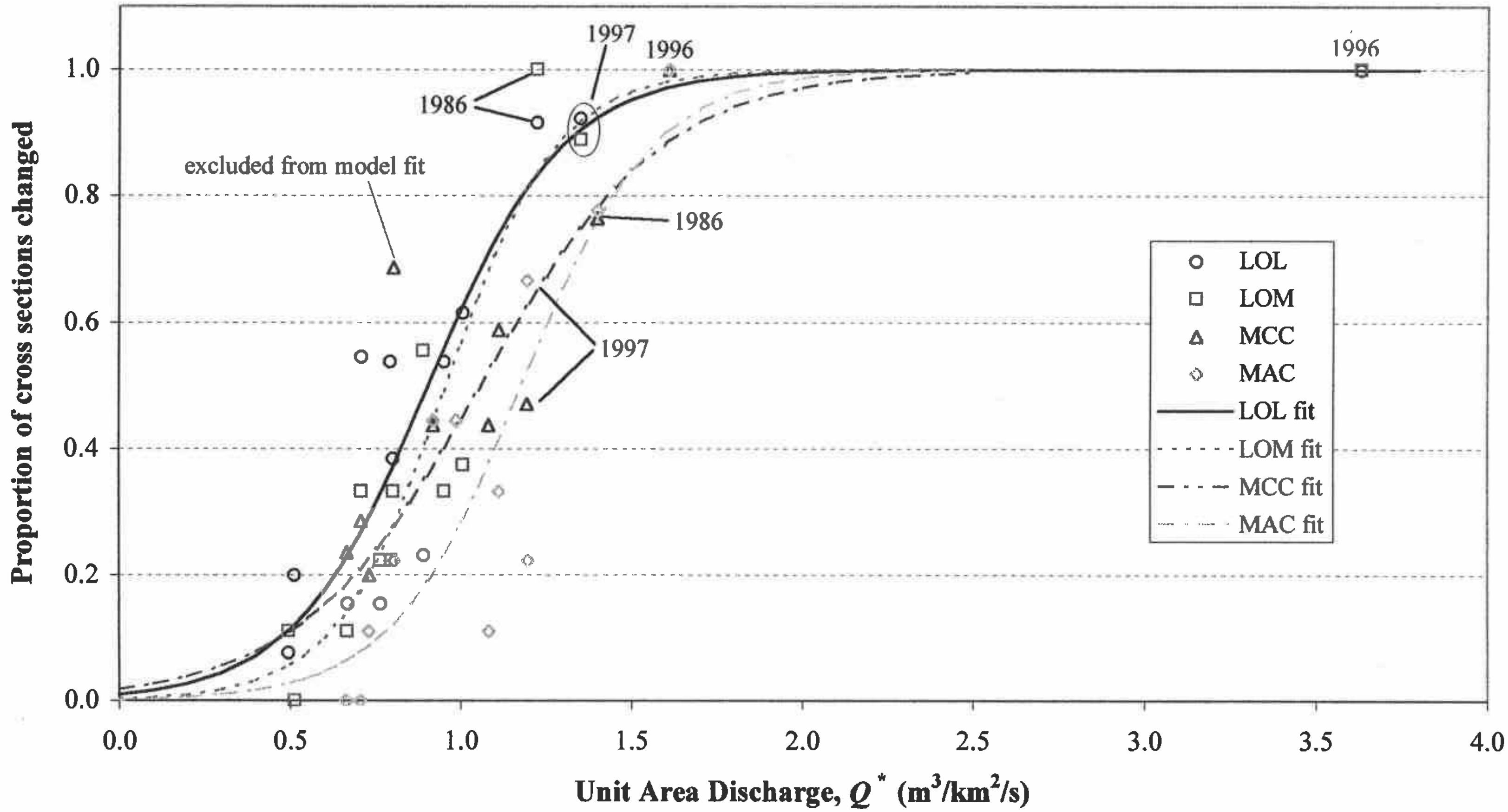


Figure 10.16. Proportion of cross sections exhibiting change versus maximum instantaneous peak unit area discharge during the interval since the previous cross section survey for Lookout and Mack Creek sites. Lines show fitted quasi-likelihood logistic regression model. One outlier (1995 data point for MCC site) was excluded prior to performing the regression analysis.

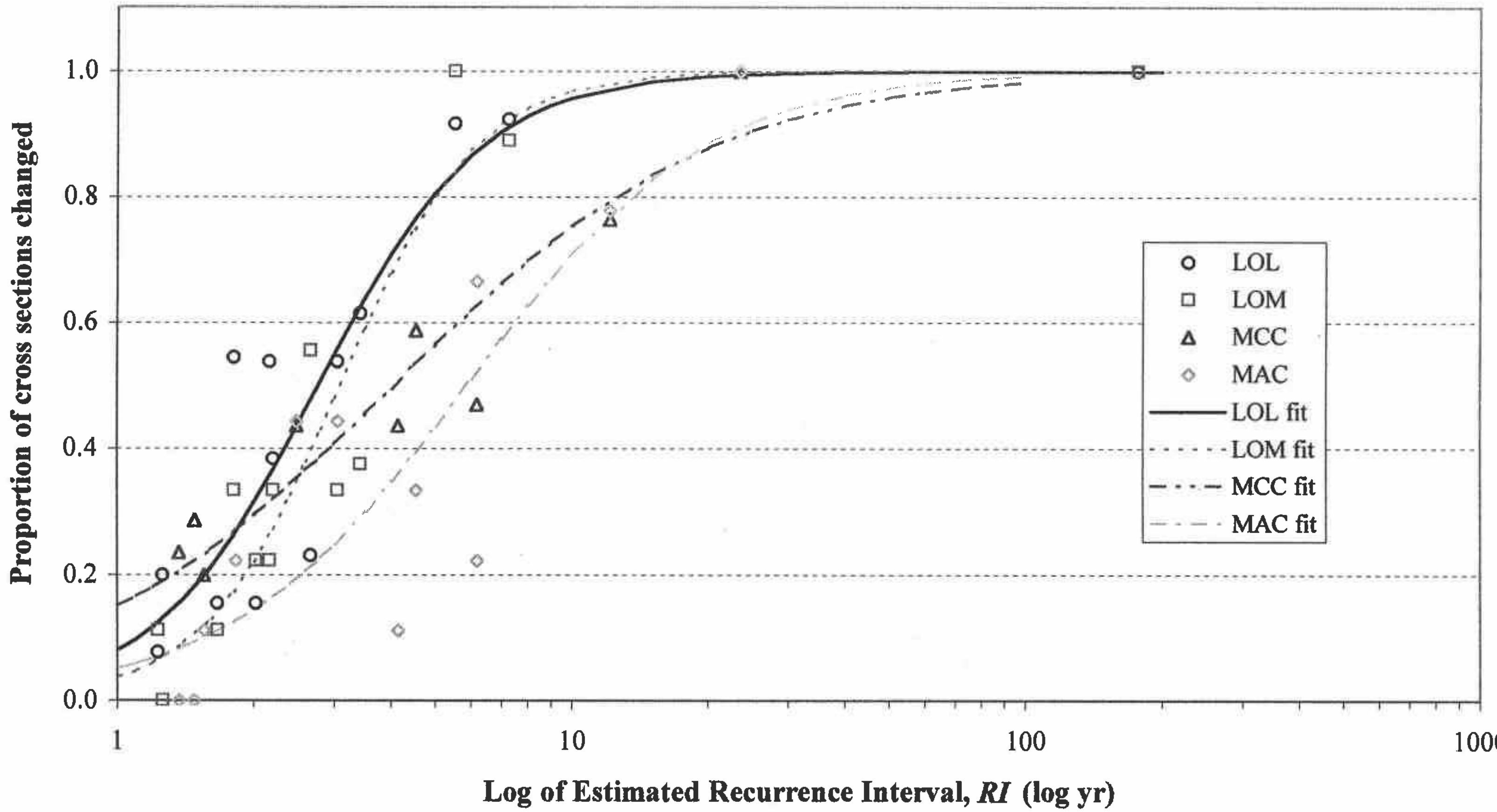


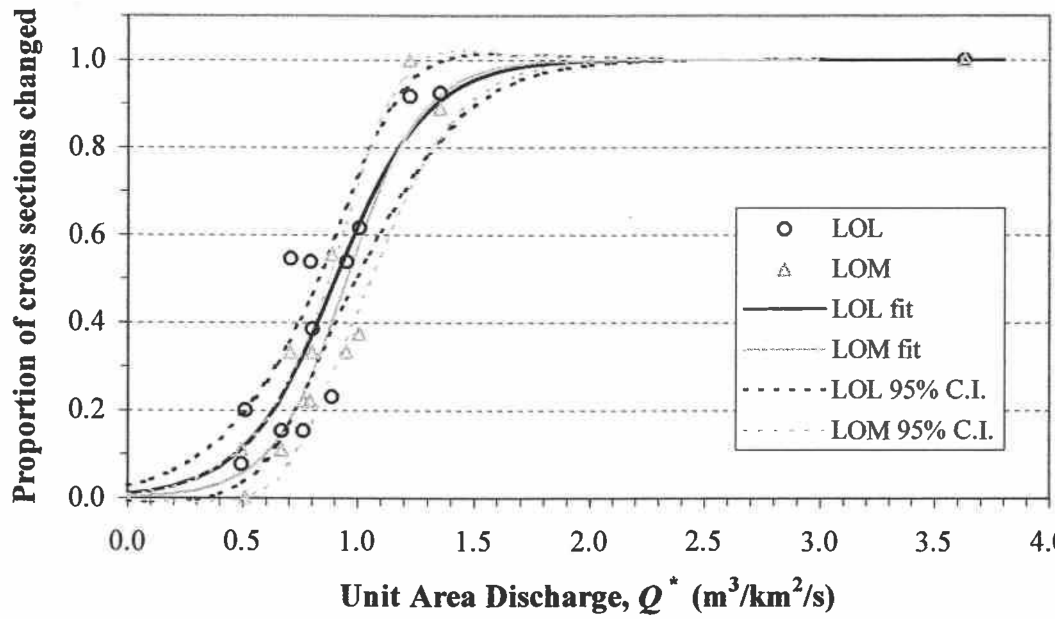
Figure 10.17. Proportion of cross sections exhibiting change versus estimated recurrence interval of maximum instantaneous peak discharge for Lookout and Mack Creek sites. Lines give quasi-likelihood logistic regression fit (using log (*RI*) and *Site* as explanatory variables.

equivalently, for Q^* values above approximately 1 $m^3/s/km^2$), but diverges slightly to the right at lower response probabilities. The response curve for the MCC site has a distinctly lower slope than the LOL, LOM, or MAC curves; it merges with the LOL curve at the low end and with the MAC curve at the high end (Figure 10.16). In general, between response probabilities of approximately 0.3 and 0.8, the unit area discharge values Q^*_p associated with any given response probability p decrease in the downstream direction. In other words, peak flow magnitudes associated with cross section response probabilities between 0.3 and 0.8 are ranked in the order LOL<LOM<MCC<MAC.

Pair-wise comparisons between sites showing the fitted response curves with approximate 95% confidence limits (Figure 10.18) make it possible to visually assess the significance of between-site differences in response probability, p, for a given value of Q^* or, conversely, differences in the value of Q^* associated with a fixed value of p. The unit area discharge Q^* associated with a given response probability p, or Q^*_p, did not differ significantly between the LOL and LOM sites for any value of p (Figure 10.18[a], Table 10.4), but Q^*_p values for both sites were significantly less than corresponding Q^*_p values for the MAC site over nearly the entire range of response probabilities (Figures 10.18 [c] and [e], Table 10.4). This suggests that a greater unit area discharge is required to produce any given probability of response at the latter site. The LOL and LOM sites also had significantly lower Q^*_p values than the Mack Creek clearcut (MCC) site for large events ($p > \sim 0.4$ for LOL and $p > \sim 0.5$ for LOM), but not for smaller events (Figure 10.18 [b] and [d]). The two Mack Creek sites differed significantly only for relatively small events ($p \leq 0.5$), for which Q^*_p was lower at the clearcut site than at the old-growth site (Figure 10.18[f]).

The cross section response probability increased over a rather narrow range of Q^* values at all four sites (Figure 10.16). At the LOM site, which has the most step-like response curve, the estimated response probability increased from 10% to 90% as Q^* increased from 0.60 to 1.31, a range 0.71 $m^3/s/km^2$ (Table 10.4[a]). At the MCC site, which has the most gradual increase in response probability with increasing discharge, the same increase in response probability from 10% to 90% was associated with an increase in Q^* from 0.47 to 1.64, a range of 1.17 $m^3/s/km^2$. However, the

(a) LOL vs. LOM



(b) LOL vs. MCC

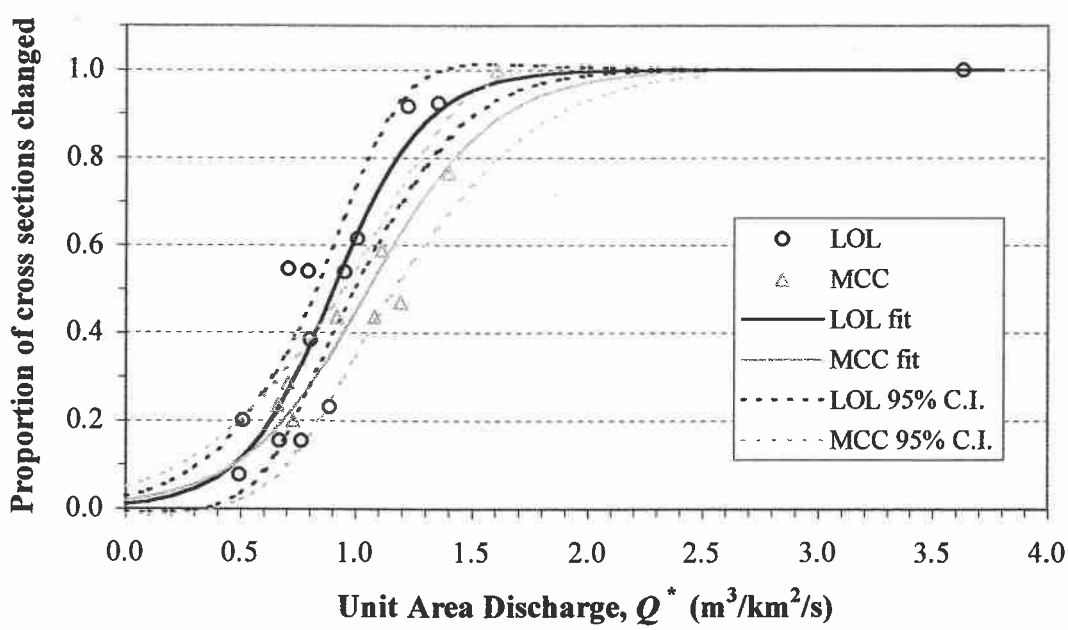
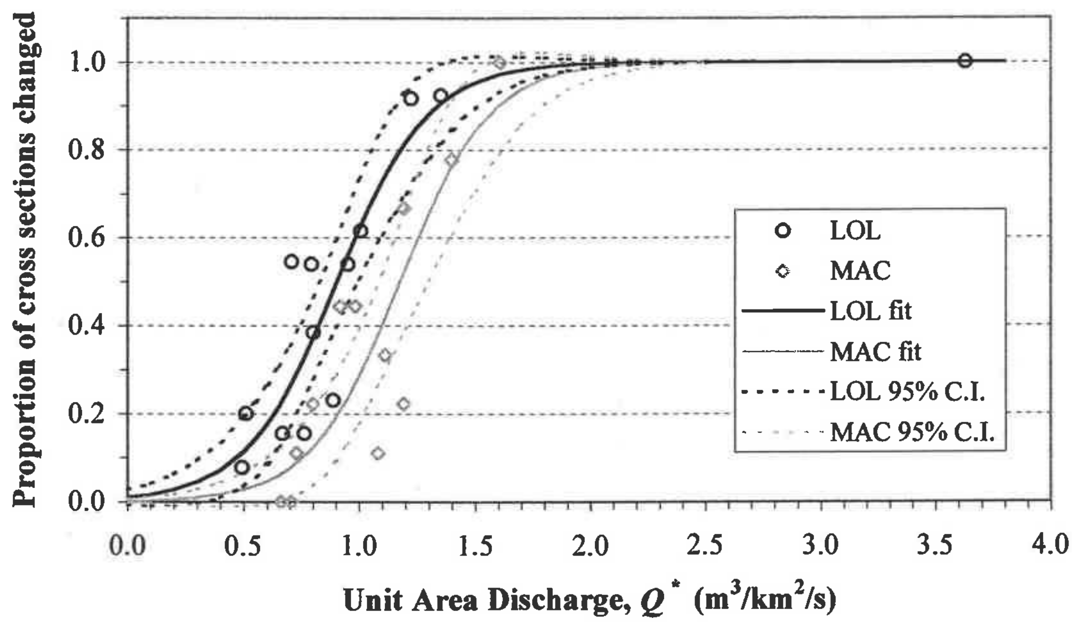


Figure 10.18. Proportion of cross sections exhibiting change versus maximum instantaneous peak unit area discharge for (a) LOL vs. LOM, (b) LOL vs. MCC, (c) LOL vs. MAC, (d) LOM vs. MCC, (e) LOM vs. MAC, and (f), MCC vs. MAC sites. Solid lines show quasi-likelihood logistic regression fit; dashed lines show approximate 95% confidence intervals (+/- 2 standard errors).

(c) LOL vs. MAC



(d) LOM vs. MCC

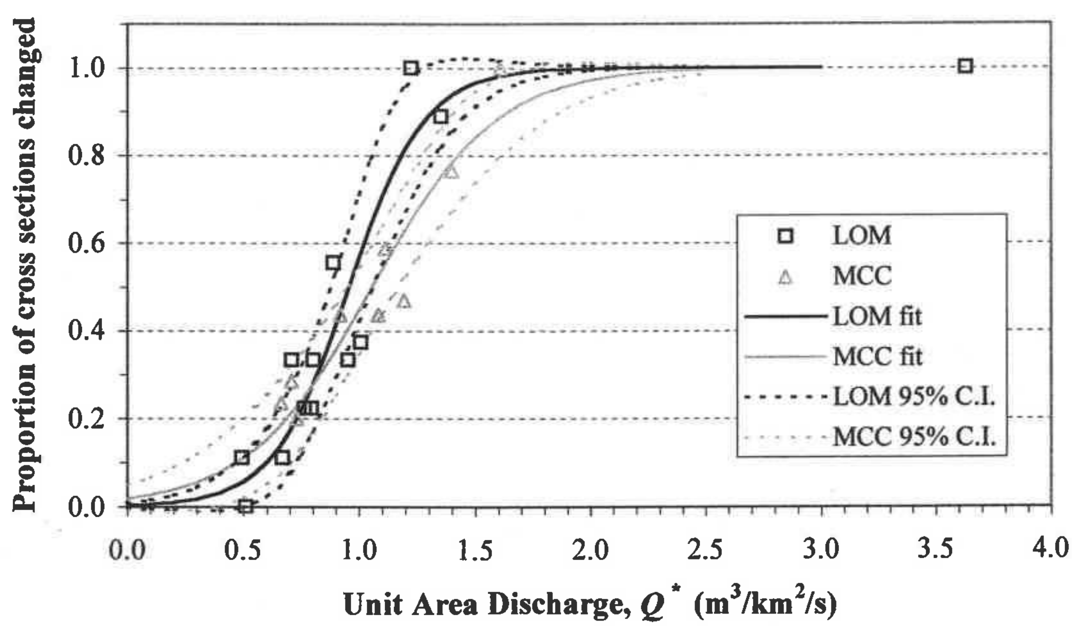
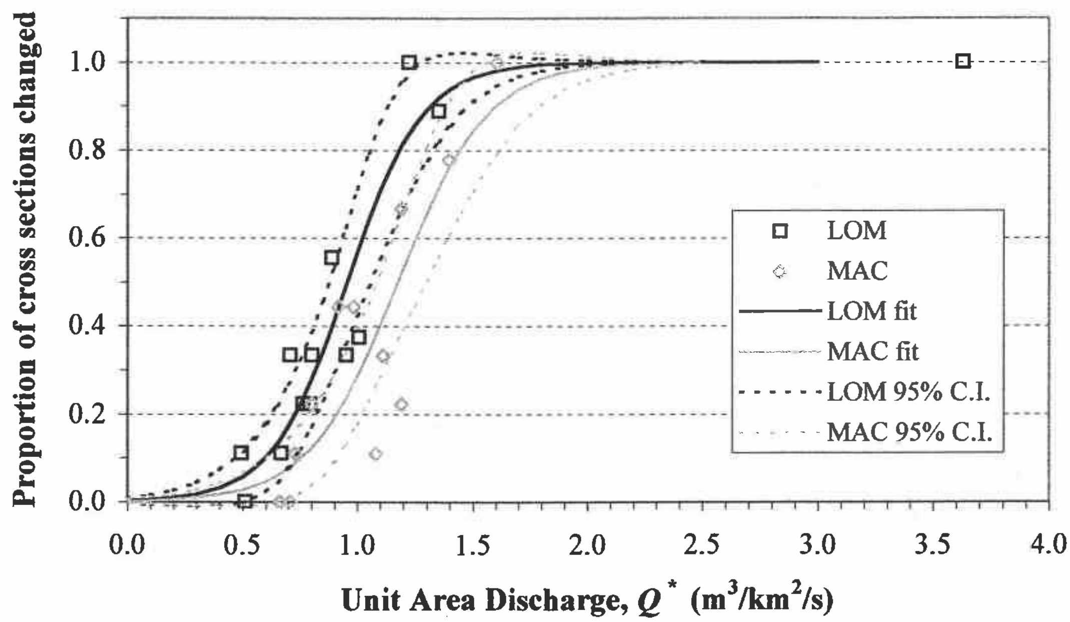


Figure 10.18 (continued)

(e) LOM vs. MAC



(f) MCC vs. MAC

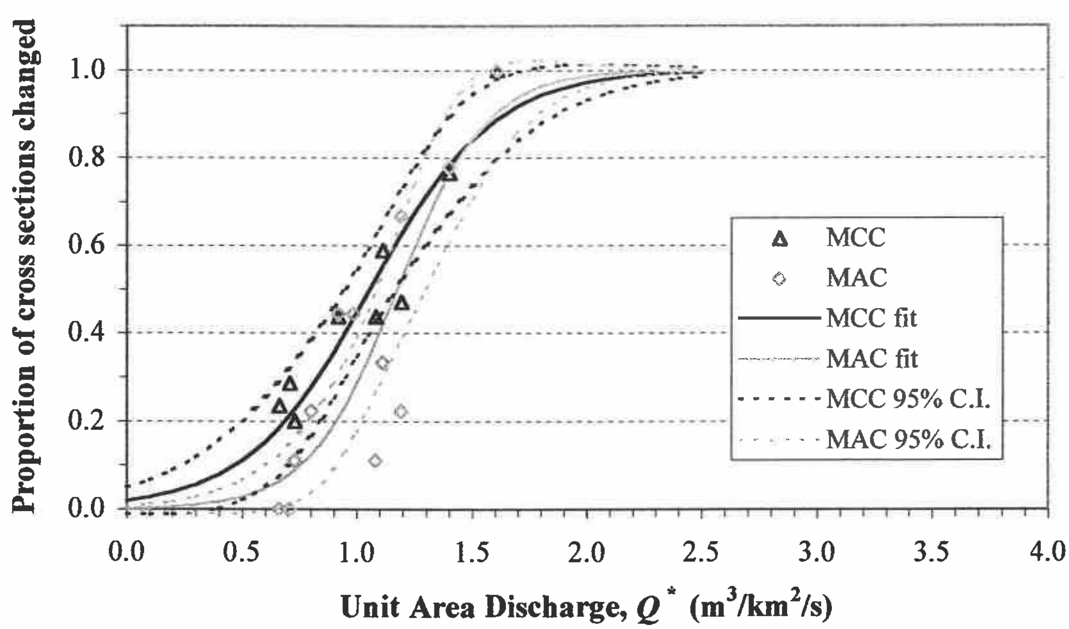


Figure 10.18 (continued)

Table 10.4 (a). Estimated values of unit area discharge ($m^3/s/km^2$) associated with selected probabilities of cross section response.

Site	Response probability, *p*														
	0.10			0.25			0.50			0.75			0.90		
	LCL	Q^*_p	UCL	LCL	Q^*_p	UCL	LCL	Q^*_p	UCL	LCL	Q^*_p	UCL	LCL	Q^*_p	UCL
LOL	0.32	0.47[a]	0.62	0.58	0.69[a]	0.77	0.83	0.90[a]	0.99	1.01	1.12[a]	1.26	1.15	1.34[a]	1.51
LOM	0.46	0.60[ab]	0.73	0.68	0.78[a]	0.87	0.88	0.96[ab]	1.06	1.02	1.14[a]	1.27	1.13	1.31[a]	1.48
MCC	0.24	0.47[a]	0.70	0.59	0.76[a]	0.90	0.95	1.06[b]	1.17	1.22	1.35[b]	1.52	1.41	1.64[b]	1.88
MAC	0.60	0.76[b]	0.91	0.85	0.97[b]	1.07	1.09	1.18[c]	1.30	1.26	1.39[b]	1.55	1.38	1.60[b]	1.79

Table 10.4 (b). Estimated values of recurrence interval (years) associated with selected probabilities of cross section response.

Site	Response probability, *p*														
	0.10			0.25			0.50			0.75			0.90		
	LCL	RI_p	UCL	LCL	RI_p	UCL	LCL	RI_p	UCL	LCL	RI_p	UCL	LCL	RI_p	UCL
LOL	<1.01	1.1[ab]	1.5	1.4	1.8[a]	2.1	2.4	2.8[a]	3.4	3.5	4.4[a]	5.9	4.6	6.9[a]	10.0
LOM	1.1	1.4[ab]	1.9	1.7	2.1[a]	2.6	2.6	3.1[ab]	3.9	3.5	4.5[a]	6.0	4.4	6.6[a]	9.3
MCC	<1.01	<1.01[a]	1.4	<1.01	1.7[a]	2.5	2.9	4.0[b]	5.7	6.5	9.8[b]	16.8	11.9	23.8[b]	48.4
MAC	<1.01	1.6[b]	2.5	2.1	3.0[b]	4.2	4.4	5.8[c]	8.6	7.5	11.3[b]	18.9	11.3	21.9[b]	40.4

Note: LCL and UCL represent approximate lower and upper confidence limits (-/+ 2 standard errors), respectively, for the estimated values of Q^*_p and RI_p. Values superscripted with the same letter are not significantly different at an approximate significance level of 0.05.

slope parameters for these two sites were not significantly different (2-sided p-value of 0.12), nor were the slope parameters for any other pair of sites (Appendix G, Table G.2[a]).

The odds of observing cross section change were estimated to increase by a factor of 21.5 (approximate 95% confidence interval: 5.3 to 87) for every 0.5 $m^3/s/km^2$ increase in Q^* at the LOM site, while at the MCC site the odds of change were estimated to increase by a factor of 6.5 (approximate 95% confidence interval: 2.7 to 16) for the same magnitude of increase in Q^* (Table 10.5[a]). Like the slope parameter upon which these estimated odds ratios are based, however, these differences are not statistically significant.

When peak flow magnitude was expressed in terms of recurrence intervals rather than Q^*, the LOL and LOM sites similarly showed a greater response for a given return period than the MAC and MCC sites (Figures 10.17, 10.19), but the difference in slope between the Mack Creek and Lookout Creek curves was greater. The estimated response probability increased significantly faster with increasing event magnitude for the MCC site relative to both the LOL and LOM sites (2-sided p-values of 0.04 and 0.02, respectively [Appendix G, Table G.2(b)]), but, as for the Q^* response curves, differences between the other sites were not significant. Estimated recurrence intervals associated with a response probability of 0.1 range from 1.0 year (MCC) to 1.6 years (MAC), while estimated recurrence intervals associated with a response probability of 0.9 range from 6.6 years (LOM) to 24 years (MCC) (Table 10.4[b]). For the LOM site, which has the steepest response curve, the odds of observing cross section change are estimated to increase by a factor of 7.5 (approximate 95% confidence interval: 2.9 to 19) for each doubling of *RI*, whereas at the MCC site, which has the flattest response curve, the estimated odds of detectable cross section change increase by a factor of 2.4 for each doubling of *RI* (approximate 95% confidence interval: 1.6 to 3.6; Table 10.5[b]). The MAC response curve has a noticeably lower slope than the LOL curve, unlike the respective response curves for Q^*, because the narrower range of Q^* values in the relatively short Mack Creek discharge record produced a more rapid increase in *RI* with increasing Q^* at Mack Creek relative to Lookout Creek (see Figure 10.7).

Table 10.5 (a). Estimated change in relative odds of observing cross section change vs. not observing change associated with a 0.5 $m^3/s/km^2$ increase in unit area discharge, Q^*, for the interval between successive cross section surveys.

Site	$\beta^{(1)}$	Std. Error	df	Odds ratio for 0.5 unit increase in Q^* mean	LCL	UCL
LOL	5.07	0.973	11	12.6	4.3	36.8
LOM	6.13	1.270	11	21.5	5.3	86.8
MCC	3.75	0.752	7	6.5	2.7	15.8
MAC	5.22	1.100	10	13.6	4.0	46.3

Table 10.5 (b). Estimated change in relative odds of observing cross section change vs. not observing change associated with a doubling of the recurrence interval of the maximum peak flow during the interval between successive cross section surveys.

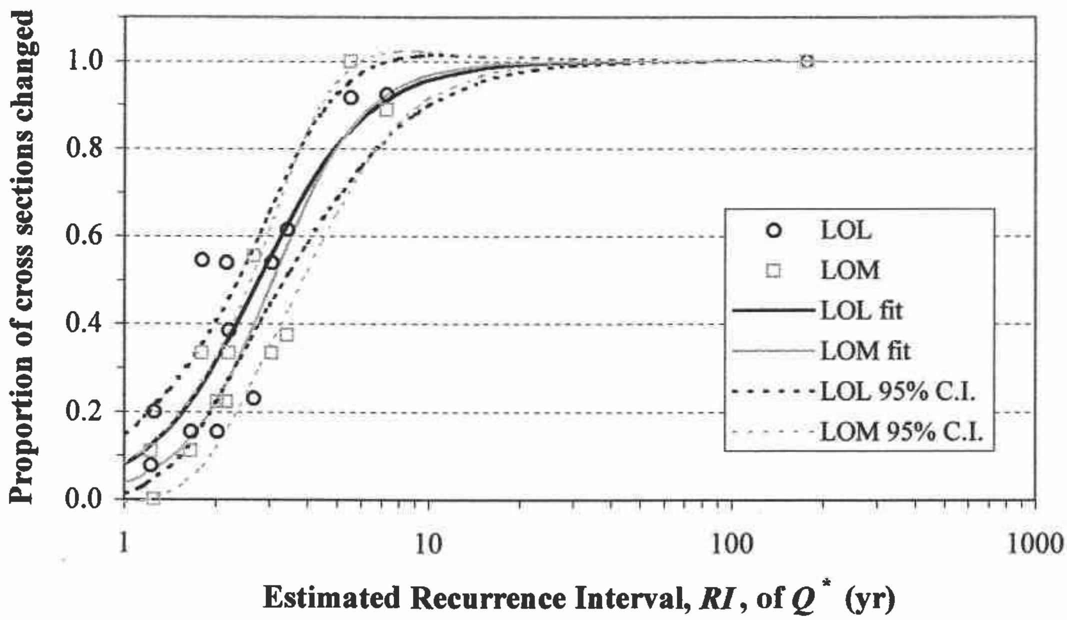
Site	$\beta^{(1)}$	Std. Err.	df	Odds ratio for doubling of recurrence interval$^{(3)}$ mean	LCL	UCL
LOL	5.56	1.076	11	5.3	2.6	10.9
LOM	6.69	1.408	11	7.5	2.9	19.0
MCC	2.86	0.578	7	2.4	1.6	3.6
MAC	3.83	0.810	10	3.2	1.8	5.5

(1) β is slope parameter from the logistic regression model fit.

(2) Value under "mean" is the estimated ratio of the odds of observing cross section change for $Q^* = X + 0.5$ $m^3/s/km^2$ (equivalent to approx. 1100 cfs at the LOL site) to the odds of observing change for $Q^* = X$ $m^3/s/km^2$. LCL and UCL are approximate lower and upper 95% confidence intervals for the odds ratio.

(3) Value under "mean" is the estimated ratio of the odds of observing cross section change for $RI = 2X$ years to the odds of observing change for $RI = X$ years. LCL and UCL are approximate lower and upper 95% confidence intervals for the odds ratio

(a) LOL vs. LOM



(b) LOL vs. MCC

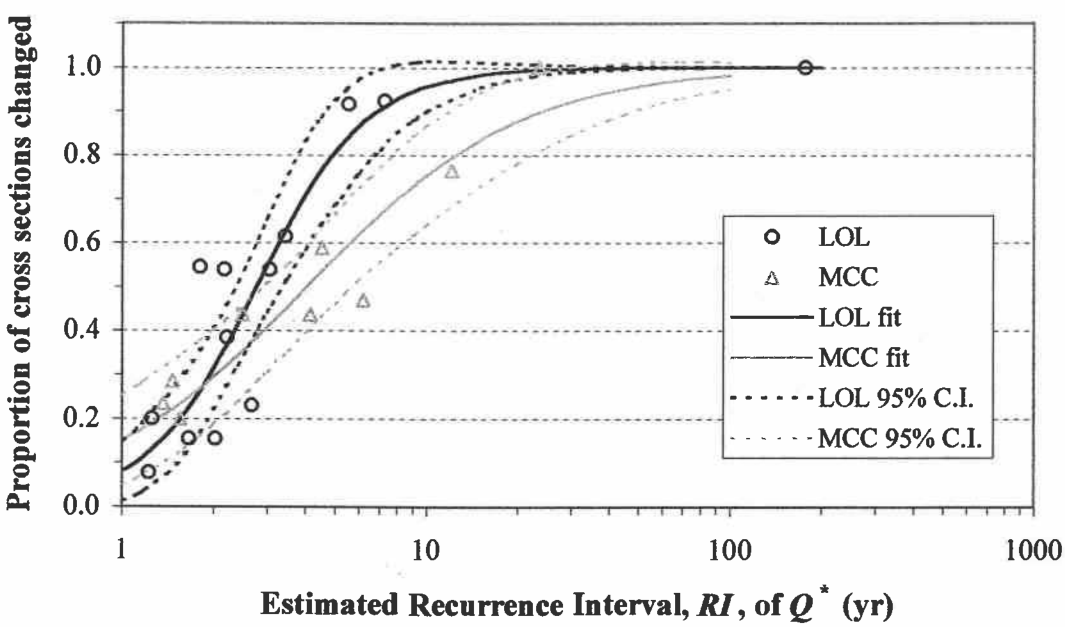
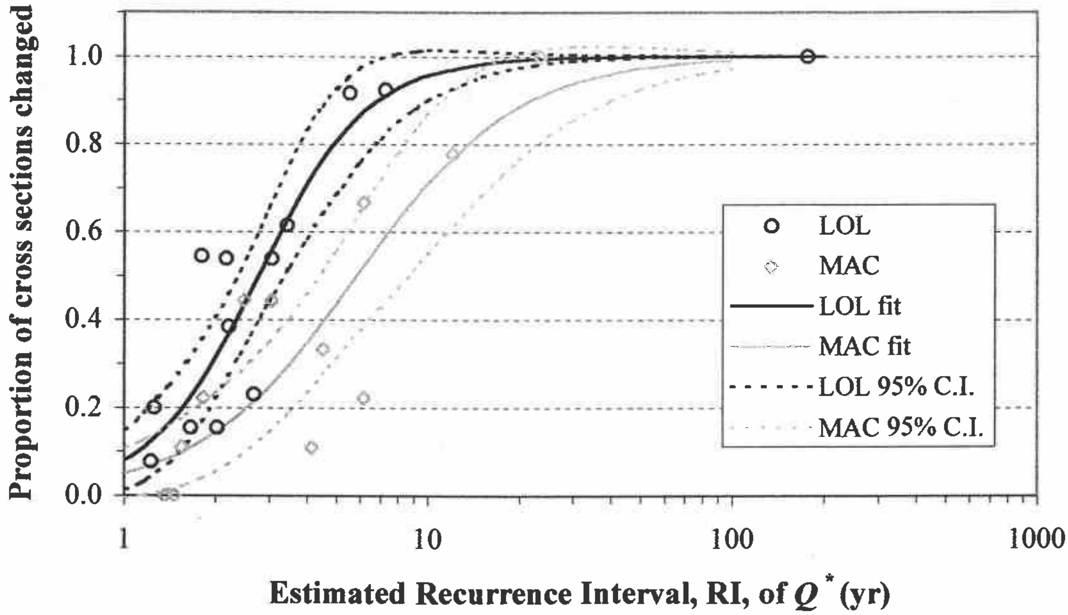


Figure 10.19. Proportion of cross sections exhibiting change versus estimated recurrence interval (RI) of maximum instantaneous peak discharge (Q^*) for (a) LOL vs. LOM and (b) LOL vs. MCC, (c) LOL vs. MAC, (d) LOM vs. MCC, (e) LOM vs. MAC, and (f) MCC vs. MAC sites. Solid lines give quasi-likelihood logistic regression fit for log *RI*; dashed lines show approximate 95% confidence intervals (+/- 2 standard errors).

(c) LOL vs. MAC



(d) LOM vs. MCC

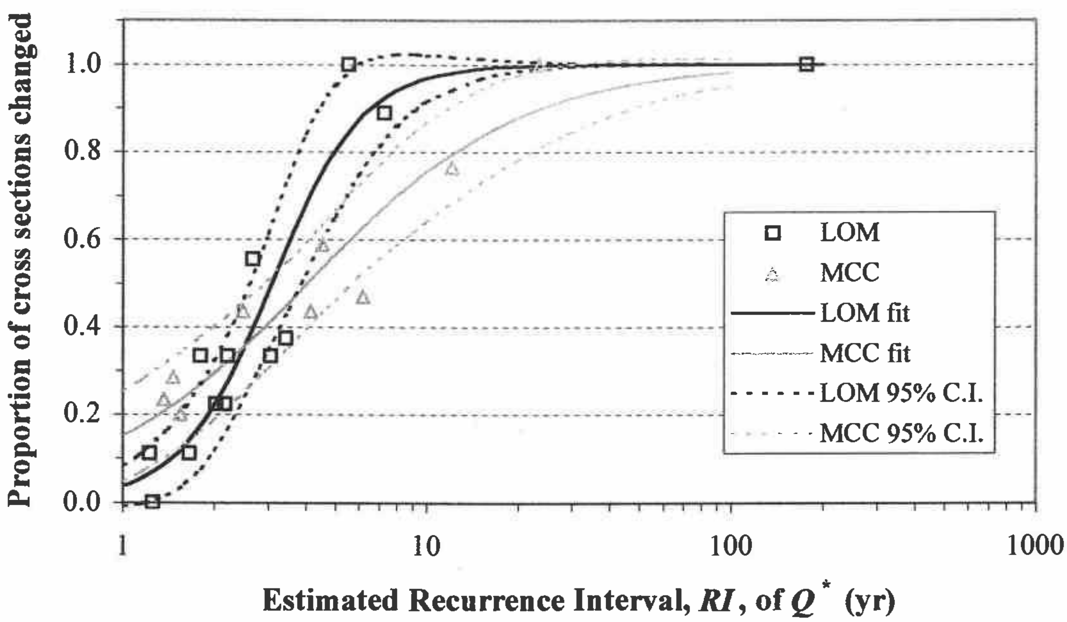
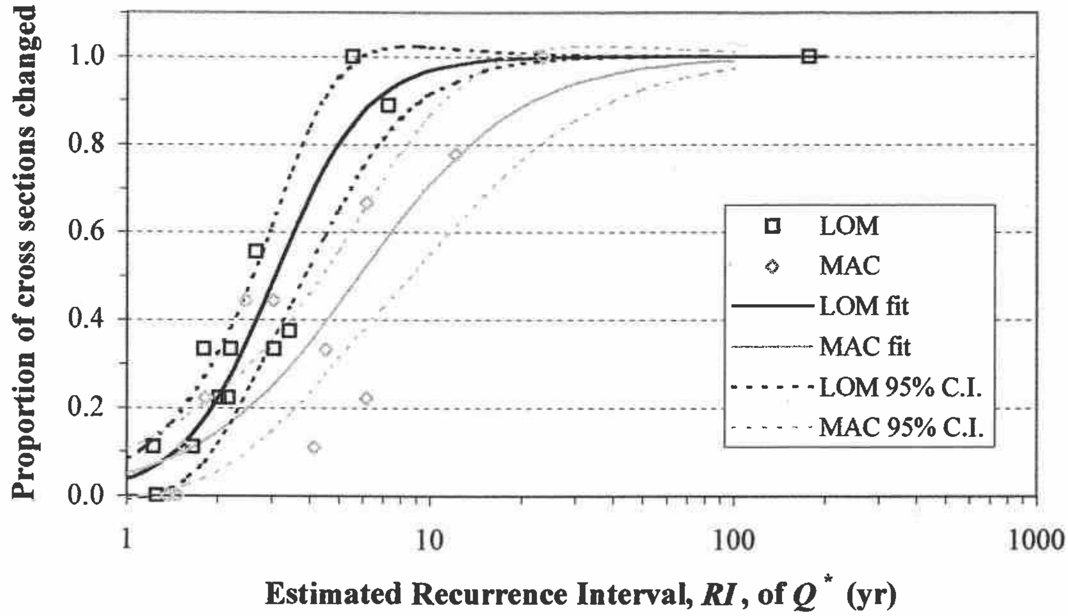


Figure 10.19 (continued)

(e) LOM vs. MAC



(f) MCC vs. MAC

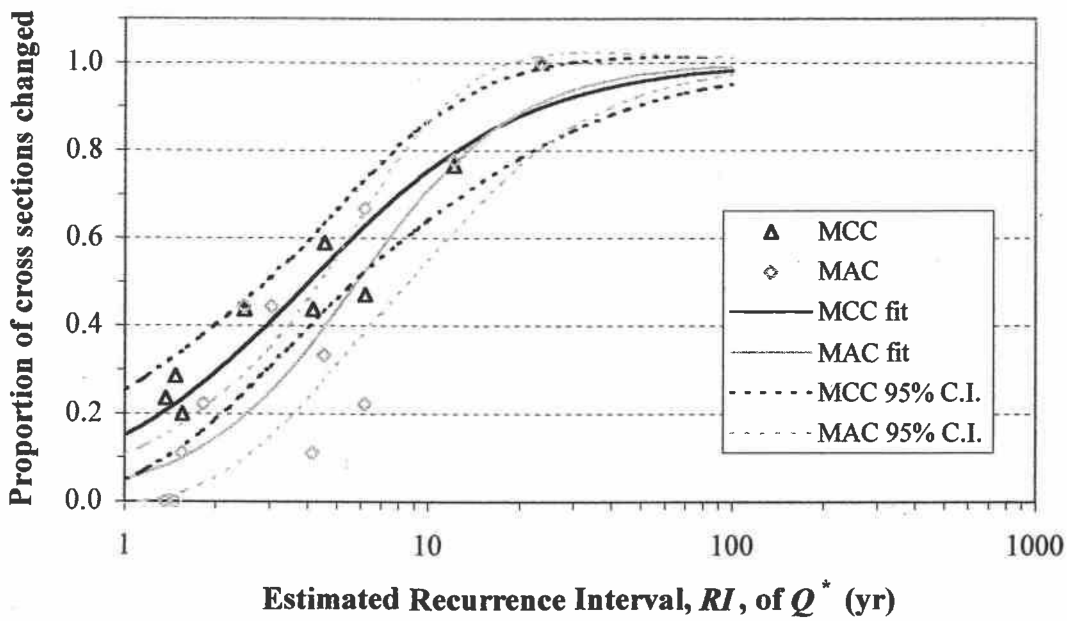


Figure 10.19 (continued)

11 Discussion

11.1 Frequency of Channel and Riparian Disturbance

The long-term cross section data analyzed in this study show that while some degree of bed mobility occurred at relatively frequent intervals at each of the study sites, large scale restructuring of the channel occurred infrequently. Flows which produced observable change in, on average, 25% of cross sections had estimated recurrence intervals of between 1.7 and 3.0 years (Table 10.4[b]); these flows did not cause significant channel change, but may represent the onset of significant bedload transport. Floods with recurrence intervals in the range of approximately 3 to 6 years (Table 10.4[b]), which produced detectable change in approximately 50% of cross sections, reworked significant portions of the channel bed at the Lookout and Mack Creek sites in a patchy fashion. Peak flows that produced detectable change at 90% of cross sections—flows able to cause significant channel adjustments—were estimated to occur approximately once every 7 years, on average, at the two 4th to 5th-order Lookout Creek sites and approximately every 23 years at the two 3rd-order Mack Creek sites (Table 10.4[b]).

The extent to which peak flows with a 5 to 7-year recurrence interval significantly modify channel morphology may vary significantly at the reach scale within mainstem 4th to 5th-order channels within the Andrews Forest. Wondzell and Swanson (1999) noted that significant changes had occurred within unconstrained reaches of 5th-order Lookout Creek following floods of this magnitude in November 1977, February 1986, and the winter of 1996-97. However, they observed little change in channel, bar or LWD configuration following peak flows with 5 to 7-year recurrence intervals in 4th-order McCrae Creek in 1990 and November 1996.

Floods that completely restructure the stream channel and cause widespread reworking of vegetated riparian surfaces are substantially more infrequent, having an estimated recurrence interval somewhere between 7 and 90 years in mainstem Lookout Creek. These values bracket Grant et al.'s (1990) hydraulically based estimate of a 25 to 50-year recurrence interval for peak flows required to rearrange channel unit structure in French Pete Creek, an 83 km^2 tributary of the South Fork McKenzie River. The December 1964 and February 1996 floods (with estimated recurrence intervals of 90 and 177 years, respectively) were clearly channel-restructuring events in Lookout Creek. However, smaller peak flows of a size that did not occur during the monitored period may also have the capacity to cause major channel restructuring. The 1964 and 1996 floods were larger than the annual peak flow for WY 1997, the next largest event during the period for which cross-section records exist, by a factor of 2.2 and 2.7, respectively (Table D.1, Appendix D). This difference is nearly as large as the 3.6-fold difference between the 1997 annual peak flow, which produced moderate, patchy channel changes in Lookout Creek, and that for WY 1994, the *smallest* annual peak flow during the cross section record (Table 10.1). Thus, there is a large range of possible peak flow magnitudes for which no observations exist between peak flows observed to cause moderate, patchy channel response and those observed to cause wholesale restructuring of the entire active channel floodway.

The results of this study are consistent with the expectation that steep, constrained channels with step-pool or cascade type reach morphology should exhibit greater stability than lower gradient mainstem channels with plane-bed or pool-riffle morphology (Figure 8.1; Montgomery and Buffington, 1997; Montgomery, 1999). The cross section data clearly demonstrate that the bed of Mack Creek at both the old-growth and clearcut sites has been reworked less frequently than that of Lookout Creek at either the LOL or LOM sites during the monitoring period (Figure 10.18 [b] through [d], Table 10.4[b]). Peak flows that caused detectable channel change at 90% of cross sections were approximately three times as frequent at the Lookout Creek sites as at the Mack Creek sites (Table 10.4[b]).

The results of this study also provide a means of assessing the likely impacts of increased peak flow magnitudes due to land use practices such as logging and associated road construction (Jones and Grant, 1996; Jones, in press) on the frequency of channel disturbance (Table 11.1). This analysis suggests that even modest increases in the magnitude of peak flows of all sizes could lead to significant increases in the frequency of channel disturbance. For example, the frequency of events

Table 11.1. Estimated effect of an increase in peak flow magnitudes on the recurrence interval and frequency of peak flows associated with selected levels of cross section response. If all peak flows were increased in magnitude by a fixed percentage, then peak flows of a fixed magnitude—e.g., the discharge required to produce a 50% or 90% cross section response probability—would become more frequent. The values in the table show what the estimated recurrence interval of peak flows associated with the specified cross section response probability under current conditions would be if peak flows were increased by the indicated percentage. Values in parentheses give the effective increase in frequency of peak flows of the specified magnitude, relative to current conditions, that would result from the indicated percentage increase in peak flow magnitudes.

	Estimated recurrence interval in years and percent increase in frequency (in parentheses)									
	Peak flows associated with 50% cross section response probability					Peak flows associated with 90% cross section response probability				
Site	current	Increase in peak flow of... 10%	25%	50%	100%	current	Increase in peak flow of... 10%	25%	50%	100%
LOL	2.8	2.3 (20%)	1.9 (48%)	1.5 (88%)	1.2 (138%)	7.1	5.4 (31%)	4.0 (78%)	2.7 (164%)	1.7 (324%)
LOM	3.1	2.5 (21%)	2.0 (52%)	1.6 (96%)	1.2 (156%)	6.8	5.1 (32%)	3.8 (77%)	2.6 (161%)	1.6 (314%)
MCC	3.8	2.8 (35%)	2.0 (89%)	1.5 (162%)	1.1 (242%)	26.0	15.9 (64%)	8.8 (197%)	4.3 (501%)	1.9 (1258%)
MAC	5.8	4.0 (45%)	2.7 (116%)	1.7 (232%)	1.2 (378%)	22.7	14.3 (59%)	8.0 (184%)	4.0 (474%)	1.8 (1153%)

associated with a 90% cross section response—events on the order of the 1986 and 1997 peak flows in Lookout Creek and the 1996 flood in Mack Creek—would increase by approximately 30% in Lookout Creek and 60% in Mack Creek in response to a 10% across-the-board increase in peak flow magnitudes (Table 11.1). A 25% increase in peak flow magnitude would result in an approximately 75% increase in the frequency of the same class of peak flows in Lookout Creek and a near tripling of the frequency in Mack Creek. If peak flows were increased by 100%, which is within the range of increases suggested by Jones and Grant (1996) for large basins such as Lookout Creek, the recurrence interval for peak flows capable of causing patchy but geomorphically significant channel changes in mainstem Lookout Creek (i.e., floods of magnitude similar to the February 1986 and November 1996 floods) would decrease from about 7 years to less than 2 years, a more than 4-fold increase in frequency (Table 11.1).

Even if the magnitudes of the peak flows with recurrence intervals of greater than 5 years are not affected by logging and roads (Thomas and Megahan, 1999), increases in the magnitude of all peak flows smaller than the 5-year flood could still have potentially significant geomorphic and ecological consequences. For example, peak flows that are associated with a 50% cross section response at the Lookout and Mack Creek cross section sites have estimated recurrence intervals of between 2.8 and 5.8 years (Table 11.1). These events are significant in terms of sediment transport and the reworking of patches of fine sediment (i.e., gravels) in pools and other in-channel storage sites. A 25% increase in the magnitude of peak flows of this size or smaller would lead to an approximately 50% increase in the frequency of events associated with a 50% cross section response in Lookout Creek and roughly a doubling of their frequency in Mack Creek (Table 11.1).

11.2 Spatial Patterns of Channel and Riparian Disturbance at the Watershed Scale

The contrasting behavior of the five cross section study sites is consistent with contemporary conceptual models of flood-related disturbance (Swanson, 1998;

Montgomery, 1999; Johnson et al., in press.; Nakamura et al., in press.) Because they are subject to different disturbance processes/mechanisms (Figure 8.1), steep, low-order tributary channels and mainstem channels exhibit distinctly different responses to both moderate and large magnitude flood-related disturbances. Steep, 1st and 2nd-order channels within the Andrews Forest exhibit limited response to moderate floods and an almost binary response to large floods—either severe debris flow disturbance or minor fluvial disturbance—that is patchy at the landscape scale. Mainstem (4th to 5th-order) channels exhibit greater response to moderate floods than do low-order tributaries and are subject to a more continuous spectrum of channel and riparian response to major floods that is patchy at the reach and finer scales. Third-order tributaries such as Mack Creek are transitional between low-order tributaries and mainstem streams in terms of disturbance mechanisms and channel response to floods.

Within the Andrews Forest, steep, low-order tributary channels with drainage areas on the order of 1 km^2 or less (e.g., Cold Creek or small watersheds 1, 2, and 3, Figure 3.1) appear to exhibit essentially a binary response to large flood events. Those channels that experience debris flows (Figure 9.1) are subject to severe channel and riparian disturbance in which the entire valley floor is thoroughly reworked (Swanson et al., 1998). The entire channel may be scoured to bedrock over much of its length (Figure 11.1), with much or all of its alluvial sediment and standing crop of both riparian trees and in-channel LWD transferred downstream to a larger tributary or mainstem channel. In contrast, small tributary channels that do not experience debris flows typically show little evidence of significant channel or riparian disturbance even following major floods (Figure 11.2). The extent of flood disturbance in these channels is largely limited to patchy reworking of the channel bed associated with fluvial bedload transport, mainly of finer, more mobile fractions of the bed material (i.e., gravel and small cobbles). Conifer logs are large relative to channel dimensions in low-order tributaries, and even large floods are typically incapable of mobilizing them. Stands of riparian alder and maple (in logged areas such as WS 1, Figure 11.2) help to stabilize the channel margins and are able to withstand flood flows in the absence of large moving logs that could be used to batter and topple riparian vegetation.

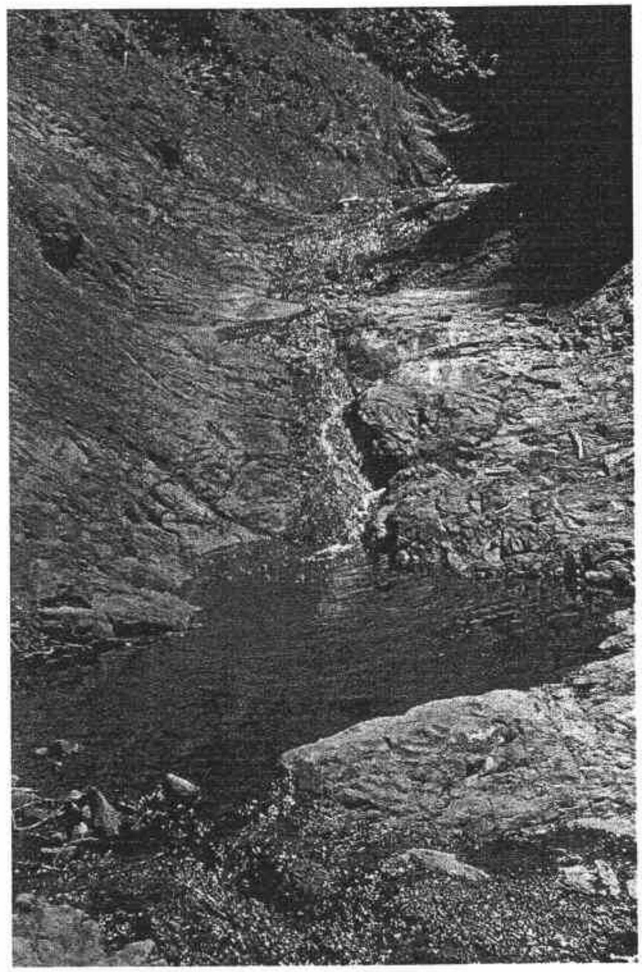


Figure 11.1. View of channel in Watershed 3 after debris flows during the February 1996 flood scoured the channel to bedrock. (Photo by F. J. Swanson, USFS)

Observations at the Cold Creek and Mack Creek sites provide evidence of a dual threshold for bed mobility in these channels, as hypothesized by the Process Domain Concept (Figure 8.1; Montgomery 1999). For example, in Cold Creek, cross section changes document significant bedload transport during the winter of 1995-96, but the presence of many mossy boulders and cobbles, as well as herbaceous vegetation, within and along the margins of the low flow channel indicates that most of the larger particles in the bed were not mobilized (Figure 9.2). The largest changes observed in 2nd-order Cold Creek in response to the February 1996 flood were associated with movement or input relatively small pieces of LWD (less than or close

(a) (b)

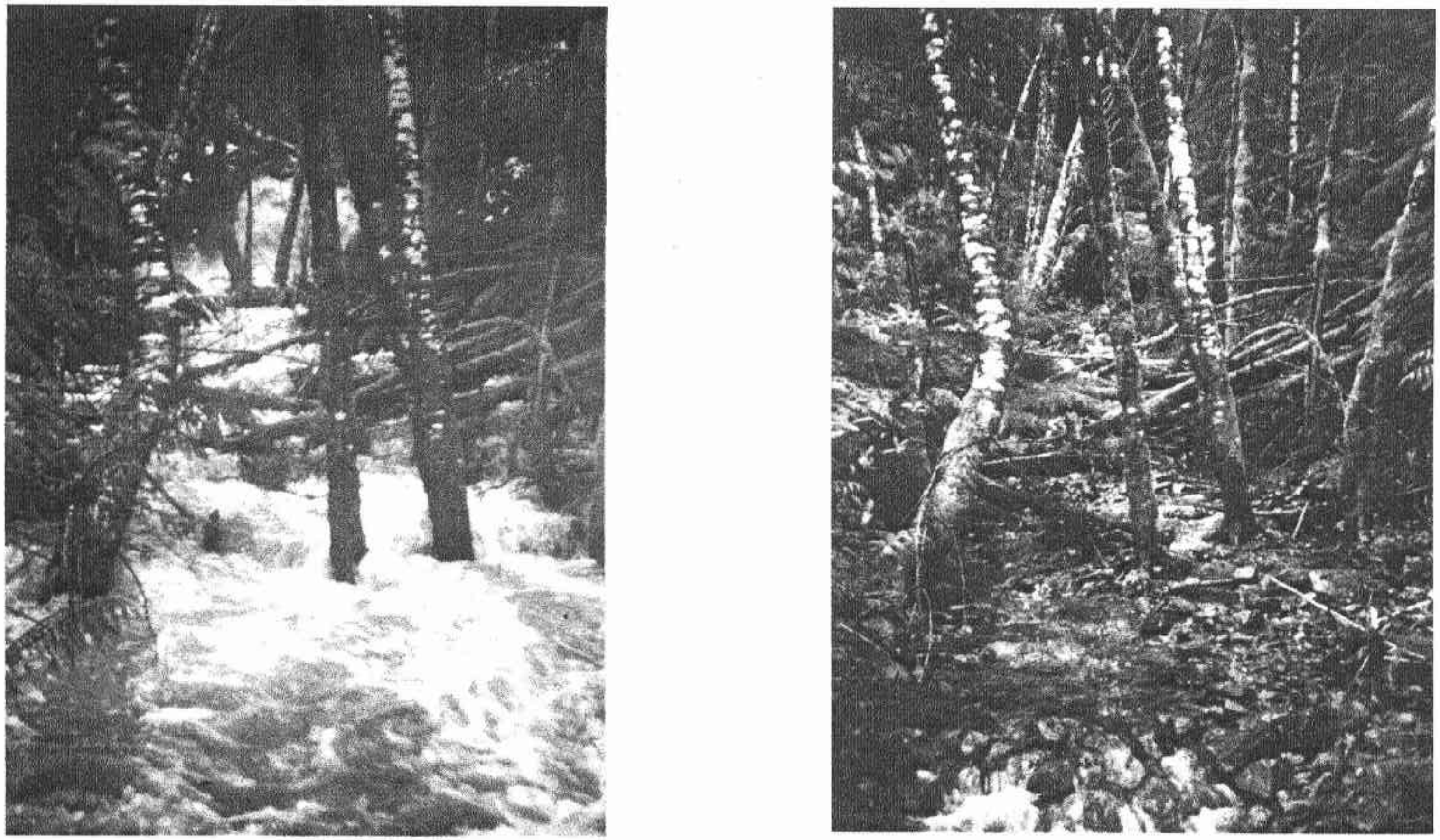


Figure 11.2. Two views of the stream channel in Watershed 1: (a) February 7, 1996 (during flood); (b) after the flood. Riparian alders and woody debris within the channel were not affected by the flood, and the channel afterwards shows no obvious evidence of the flood's passage. (Photos by F. J. Swanson, USFS)

to the channel width in length) which created or destroyed small step structures (Figure 9.2) by capturing or releasing gravel and small cobbles. Because of the steep slope of low-order channels, the effects of such occurrences on channel form were quite localized.

The February 1996 flood produced a greater degree of channel response at the Mack Creek sites than the Cold Creek sites, but the available evidence also supports a dual mobility threshold in Mack Creek. The 1996 flood appears to have been close to the threshold for mobilizing large framework bed particles in Mack Creek, but not sufficiently large to generally restructure the channel. Cross section data document the movement of boulders on the order of 1-m diameter within the channel thalweg during the 1996 flood, and photographic evidence documents movement of boulders of similar size during the 1986 flood (Grant et al., 1990), which was nearly as large as the 1996 flood in Mack Creek (Table 10.1). However, the presence of many mossy undisturbed boulders and large cobbles within the channel at the old-growth site (Figure 4.3; lack of a riparian forest canopy limits moss growth within the clearcut reach), together with the relatively undisturbed riparian vegetation at both the old-growth and clearcut sites (Figures 4.3 and 9.4), suggests that mobilization of large framework bed particles was patchy and limited to the channel thalweg. The extensive cross section changes observed, on the other hand, indicate that smaller bed material (i.e., gravel and cobbles) was mobilized across the entire active channel floodway width.

In steep, constrained channels that do not experience debris flows, bank erosion and lateral shifts of the low flow channel did not appear to be a common channel response. No evidence of significant bank erosion or lateral channel shifts has been documented by the cross sections at either the Mack Creek or Cold Creek sites, nor was much evidence of recent bank erosion observed during mapping of these reaches following the 1996 flood. However, locally widening of the channel and occurrence of scoured, over-steepened banks at the margins of channel-spanning LWD jams at the Mack Creek old-growth reach suggests that localized bank erosion has occurred in association with these structures. Also, slightly undercut but stable banks are common at the Cold Creek site, suggesting modest chronic or infrequent bank erosion.

Mainstem channels within the Andrews Forest (e.g., the LOL and LOM sites) exhibit a more continuous spectrum of response to floods than do low-order tributary channels; small patches of channel change in small floods become larger and coalesce in reaches at higher flows, and at the highest flows, all patches of change are connected, producing wholesale channel change. In moderately large floods with recurrence intervals on the order of 5 to 10 years, such as occurred in the 1986 and 1997 water years, there was patchy reworking of the bed and associated changes in channel form at the channel unit scale. Some LWD was mobilized (Figure 8.2), contributing to moderate, patchy riparian disturbance. However, in major floods, mainstem channels are subject to large pulse inputs of sediment and LWD from debris flows in multiple tributaries (Figures 8.2, 9.1). A total 24 documented debris flows entered 4th and 5th-order McCrae and Lookout Creeks during the period from 1946 to 1996, nearly all of which occurred during the 1964 and 1996 floods (Snyder, in preparation). Riparian landslides and slump failures at earthflow toes are also sources of potentially large pulse inputs of LWD and sediment to mainstem channels during large floods (Nakamura et al., in press). These pulse inputs of sediment and LWD contribute to channel and riparian disturbances that are patchy at the reach scale. For example, both the lower and middle Lookout Creek cross section sites exhibited reach-scale channel changes in 1996—aggradation at middle Lookout Creek and a lateral channel shift involving abandonment of one channel and scouring of a new one at lower Lookout Creek. In more severely impacted reaches, the bed and adjacent alluvial deposits may be reworked across the entire active channel floodway, as occurred at both these sites in 1996.

In contrast with low-order tributaries such as Cold Creek and Mack Creek, bank erosion and lateral channel migration within the active channel floodway are prominent forms of channel response to large floods in unconstrained mainstem reaches, consistent with the Process Domain Concept (Figure 8.1). For example, portions of both the LOM and LOL sites exhibited both significant bank erosion and significant lateral shifts in the position of the channel thalweg in response to the 1996 flood (Sections 10.2.3 and 10.2.4). (While the LOL reach is moderately constrained [Table 9.1], the bank erosion and lateral channel shift in this reach occurred downstream of a bedrock constrained bend at XS 9 [Figure 9.8], where the active channel floodway widens abruptly.) Prior to the 1996 flood, the only evidence of bank erosion provided by the cross section data was localized bank recession at XS 6 at the LOL site between 1981 and 1982 (Appendix B), which appeared to be associated with input of four key LWD pieces to the channel (Figure 10.12[a] and [b]). Nakamura and Swanson (1993) attributed the input of these LWD pieces to windthrow and bank erosion in the winter of 1981-82. Like bank erosion, large-scale lateral channel shifts are also absent from the cross section record other than in 1996.

In contrast with observations at the cross section sites, Johnson et al. (in press) present evidence of relatively frequent lateral channel shifts in some unconstrained 4th and 5th-order reaches of Lookout Creek. They present a series of plan view maps (Figure 11.3) based on aerial photographic analysis for a section of Lookout Creek immediately downstream of the McCrae Creek junction (i.e., between LOM and LOL; Figure 3.1). These maps show a dramatic widening of the active channel floodway at the expense of adjacent conifer forest between 1959 and 1967 in response to the floods of December 1964 and January 1965 (Figure 11.3), implying major bank erosion. The location of the junction of Lookout and McCrae Creeks shifted downstream (toward the bottom of Figure 11.3), and the position of the low-flow channel in Lookout Creek upstream of the junction shifted to the south (toward the right in Figure 11.3), while downstream of the junction the multiple-thread 1959 channel was simplified to a single thread in 1967 as the creek abandoned two previously active low-flow channels. Significant bank erosion and lateral channel shifts also occurred between 1989 and 1996, presumably in response to the February 1996 flood. At the upper (east) and lower (west) ends of this reach, the channel cut southward into portions of coniferous floodplain which had not been disturbed by the 1964 flood, and the low-flow channel shifted to opposite sides of the floodway in the lower half of the reach during this period.

During periods in which major debris-flow producing flood events did not occur, little if any significant bank erosion occurred in the approximately 250-m reach

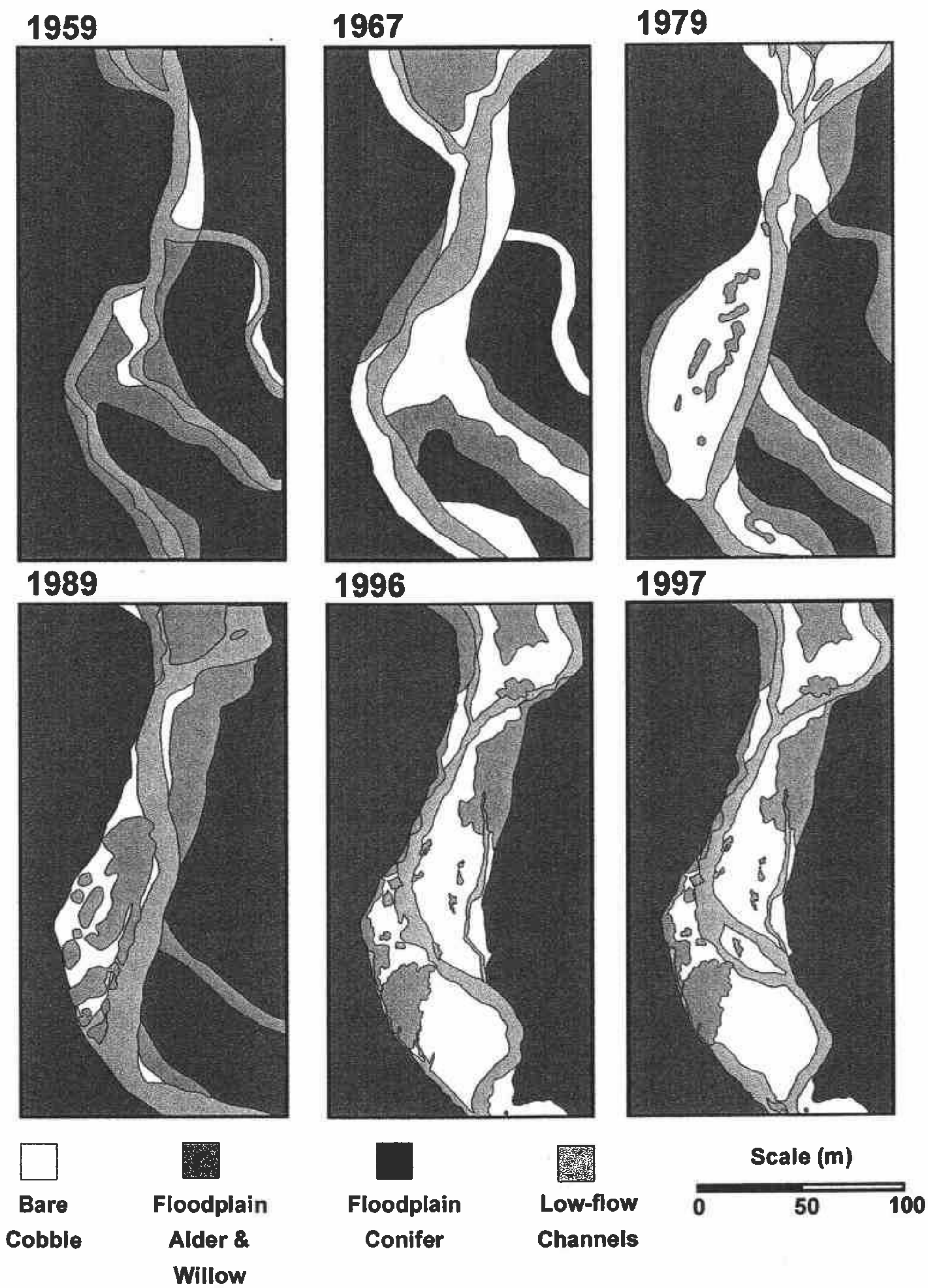


Figure 11.3. Time series of channel plan form maps for a portion of Lookout Creek immediately downstream of the McCrae Creek junction. The active channel floodway (low-flow channel, bare cobble, and floodplain alder & willow) was widened dramatically by the flood of December 1964. Channel widening occurred in the downstream end of the reach (toward bottom of map) in response to the flood of February 1996. Lateral shifts in the position of the low-flow channel occurred in response to both the 1964 and 1996 floods, as well as between 1967 and 1979 and between 1996 and 1997. (Source: Johnson et al., in press.)

of Lookout Creek represented in Figure 11.3. However, large-scale shifts in the position of the low-flow channel did occur between 1967 and 1979, a period which included moderately large floods (18.5- and 7.7-year recurrence interval, respectively) in January 1972 and November 1977. Smaller changes in the configuration of the low-flow channel also occurred between 1996 and 1997, a period which included several moderately large floods with estimated recurrence intervals of up to 7.3 years. These flood events were large enough to mobilize large logs within the channel in this reach (not shown in Figure 11.3), which likely facilitated the observed lateral channel shift within the active floodway.

11.3 Role of LWD in Channel and Riparian Dynamics

Because LWD seldom moves (Keller and Swanson, 1979; Nakamura and Swanson, 1993), increases hydraulic roughness (Buffington, 1995) and provides sediment storage sites that are probably more stable than other in-channel storage sites (Thompson, 1995), it decreases sediment transport efficiency and increases channel stability in low-order channels. The response of the channel to the February 1996 flood at the Mack Creek old-growth and clearcut sites clearly demonstrates the stabilizing effects of LWD. The clearcut reach, which lacks significant quantities of in-channel LWD, exhibited predominantly substantial scour (Figure 4.5[b]) accompanied by a significant increase in the median particle diameter. In contrast, the old-growth reach, which has abundant LWD (Figure 3.2), exhibited substantial deposition of predominantly relatively fine sediment (gravel and small cobble) upstream of three channel-spanning LWD structures and moderate scour or little channel response elsewhere (Figure 4.5[a]), with no change in median particle size. Thus, the clearcut reach experienced a net loss of sediment, particularly in the gravel to small cobble size range, while in the old-growth reach there was redistribution of sediment but no evidence of net loss of sediment.

Recently input LWD may have contributed to channel changes at Mack Creek in 1996. While the February 1986 flood was nearly as large as the 1996 flood in Mack Creek and time-lapse photography within the old-growth reach documents movement of boulders 0.5 to 1 m in diameter during this flood (Grant et al., 1990), the 1986 flood caused much less channel disturbance than did the 1996 flood (Figure 10.14). One explanation for the greater observed channel response to the 1996 flood in the old-growth reach may be that a large amount of new LWD was input to the channel as a result of windthrow event in December 1995 (Gregory, personal communication). While little of this new wood moved during the February 1996 flood (S. V. Gregory, unpublished data), much of it was in position to interact strongly with flow and sediment during the flood. In the clearcut reach, the effect of the February 1996 flood may have been enhanced by the fact that it was the first large flood following the removal of a culvert at the road crossing between the clearcut and old-growth sites in the summer of 1994, when it was replaced by a bridge. The removal of the culvert may have released a significant quantity of sediment stored upstream of the road crossing, which may also be a factor contributing to the scour observed at the two lowermost cross sections in the old-growth reach.

In large (4^{th} to 5^{th}-order) channels, LWD is more mobile and generally exerts less of an influence on channel structure. An exception to this is where large, channel-spanning LWD jams form. Channel-spanning LWD structures are much less frequent in mainstem channels than in low-order tributaries (Marston, 1980), but where they do occur they can form significant steps in the longitudinal channel profile and anchor large sediment accumulations. More typically, particularly in wide, unconstrained reaches, large conifer logs or accumulations of LWD along the channel margins can anchor or protect upstream and/or downstream sediment deposits in the form of lateral bars (Figure 9.6). Rootwads can substantially increase the stability of logs within the channel (Braudrick and Grant, 2000), both by increasing drag and by elevating the bole above the bed so that a greater flow depth is required to float the log. Old-growth conifer logs with rootwads are the most stable, especially if the rootwad remains on the floodplain rather than in the channel. This study and others (Swanson et al., 1998; Wondzell and Swanson, 1999) indicate that in 4^{th} and 5^{th}-order Lookout Creek, mobilization of old-growth logs with rootwads appears to require a flood with a recurrence interval on the order of 25-100 years.

LWD that moves or is newly input to a reach during a flood plays several important roles as an agent of channel and riparian disturbance. While in transport, large conifer logs can topple riparian vegetation and batter streambanks (Swanson et al., 1998; Johnson et al., in press). Where deposited by flood flows or input from adjacent forest, these key LWD pieces can facilitate deposition of sediment both up- and downstream, which happened with key logs deposited by the February 1996 flood at the LOM site in the vicinity of XS 4 and a marginal LWD accumulation at XS 1 (Figure 9.6, locations A and B, respectively.). Conversely, where LWD is mobilized, it is likely that associated sediment will also be mobilized, resulting in channel scour. Mobilization of logs that "armor" a portion of streambank can lead to bank erosion, as occurred in the vicinity of XS 4 and 5 at the LOL site when a large conifer log lying on the west bank was floated downstream by the February 1996 flood (compare Figure 10.12 [c] and [d])

Key pieces of LWD that are transported during a flood also provide an important mechanism for lateral switching of flow between low-flow channels in unconstrained reaches that have multiple active and inactive channels (e.g., Figure 11.3) (Wondzell and Swanson, 1999; Gottesfeld and Johnson-Gottesfeld, 1990). This function is clearly indicated by the presence of LWD and often associated sediment deposits at the entrances to secondary or abandoned channels within the active channel floodway or in adjacent forested floodplain, which is a common occurrence in unconstrained portions of mainstem Lookout Creek. This suggests that LWD can "de-activate" a channel by partially or completely blocking the entrance and diverting flow, while promoting sediment deposition in the channel entrance by decreasing flow velocity there. Such a mechanism *may* have been responsible for the lateral channel shift at the lower Lookout Creek site during the 1996 flood (Figure 9.8). Video footage of the site taken on the morning of February 7, 1996 shortly before the flood peak (Grand and Swanson, 1996) shows an accumulation of LWD at the entrance to the now abandoned channel along the west bank of Lookout Creek upstream of XS 8. However, no LWD remained at this location after the flood, and at the time the video footage was taken flow had already shifted to the new, deeper channel along the east bank. Thus, it is unclear whether the LWD was responsible for deposition of the plug of boulders and large cobbles which now block the head of this channel.

Deposition or breaching of channel-spanning LWD jams in large channels is often associated with reach-scale aggradation or scour, respectively. Channel changes at the LOM site, where the channel aggraded for at least 170 m upstream of a newly formed LWD jam at XS 9 during the 1996 flood (Figure 9.6, location C), is an example of the former case. An example of the latter case occurred in 4th-order McCrae Creek during the 1996 flood, where a wood-rich flood pulse resulting from an upstream tributary debris flow breached several channel-spanning LWD jams (Wondzell and Swanson, 1999). At one location where two closely spaced LWD jams were breached, channel degradation extended more than 150 m upstream, with a maximum scour depth of approximately 2 m immediately upstream of the former LWD jam location, and decreasing scour depth in the upstream directions (Wondzell and Swanson, 1999).

11.4 Trajectories of Channel and Riparian Disturbance Through Time: Cycles vs. Threshold Shifts

Two distinct patterns of channel change over time have occurred in Lookout Creek in the past two decades: cyclical change and threshold shifts. Historical maps and cross section data for the portion of the lower Lookout Creek site immediately downstream of the bedrock-constrained bend (Figure 10.12) suggest a cyclical pattern of channel and riparian development through time at this location. The channel was reset by the December 1964 flood, in which numerous upstream tributary debris flows contributed large quantities of old-growth logs and sediment to the channel (Grant and Swanson, 1995), removing essentially all riparian vegetation within the channel floodway and transporting large in-channel LWD downstream or onto the banks or adjacent forested floodplain. By 1977, there was still very little LWD in the channel (Figure 10.12[a]), and little riparian vegetation had become established due to large peak flows in January 1972 and November 1977 (Figure 10.1[b]). By 1984 (Figure 10.12[b]), several old-growth logs had fallen into the channel from the west bank, and a number of smaller logs had also fallen or floated into the reach, some of them accumulating around the old-growth logs. Riparian vegetation—principally willow and alder—had begun to colonize the bars. By 1990, additional LWD had accumulated in the channel, and the channel had become considerably more complex, with several low-flow channels cutting across a large central bar between XS 6 and 8 (Figure 10.12[c]).

The February 1996 flood again reworked the entire channel floodway, removing nearly all the riparian vegetation and LWD from the channel and straightening and simplifying the channel plan form. Old-growth conifer trees and snags remain plentiful on both sides of the channel in this reach, and it is likely that, in the coming years, some of these will fall into the channel, beginning a new cycle of gradually increasing quantity of LWD within the channel, accompanied by re-establishment of riparian vegetation (alder and willow are already becoming re-established on the large central bar) and perhaps an increasingly complex channel form.

In contrast, the temporal pattern of channel and riparian disturbance in the Lookout Creek channel downstream of the junction with McCrae Creek is better characterized as a one-time shift than as a cyclical pattern (Figure 11.3). The December 1964 flood dramatically widened the active channel floodway at the expense of the adjacent mature to old-growth conifer forest. Because it takes on the order of a century to re-establish mature conifer forest, this magnitude of disturbance clearly has a long-term legacy.

As a result of increased channel width, it is likely that the channel and riparian zone became much more dynamic—i.e., more susceptible to frequent disturbance—following the December 1964 flood in this reach. Although riparian alder and willow became re-established relatively quickly in the newly widened riparian zone (Figure 11.3), these are not enough to prevent large conifer logs which enter the channel (not shown in Figure 11.3) from being mobilized during large floods. The effective increase in channel width greatly increases the mobility of LWD within the channel, which in turn leads to greater disturbance of riparian vegetation and greater likelihood of scour, deposition, and lateral channel shifts associated with movement of LWD interacting with sediment during floods. As a result, the reach downstream of the McCrae Creek confluence is among the most dynamic sections of channel within the Lookout Creek watershed. While historical data are not available to document how the channel responded to floods prior to 1964, at the very least it is clear that a greater portion of the valley bottom is subject to relatively frequent flood-related disturbance than was the case previously.

Thus, it appears the December 1964 flood caused a disturbance of such a magnitude in this reach that it changed the nature of the channel and riparian disturbance regime. Similar dramatic increases in the width of the riparian canopy gap were a common response to the flood of 1964 in channels throughout the region (Lyons and Beschta, 1983; Grant et al., 1985). Grant et al. (1985) and Grant (1986) found that most of these riparian openings were associated with landslides or debris flows. Although streamflow records for Lookout Creek and other Cascade streams do not exist prior to about 1950, three floods of similar or greater magnitude occurred in the 1940s in the Willamette River (measured at the Albany gage), and several much larger floods were recorded in the latter part of the 19th century (1861, 1881, and 1890) at the Albany gage. Clearly, these earlier floods did not cause the magnitude of disturbance in Lookout Creek and other Cascade channels that the 1964 flood did, because much of the conifer forest obliterated by the latter flood was much older than these previous floods.

Apparently, the 1964 flood exceeded a landscape-level disturbance threshold that previous floods of similar or larger magnitude did not reach. Since logging in the Andrews Forest and much of the western Cascades was at its peak at this time (Jones and Grant, 1996), and since a majority of the landslides and debris flows that contributed to the effectiveness of the flood originated either within clearcuts or road rights-of-way (Lyons and Beschta, 1983; Grant, 1986), it is difficult to escape the conclusion that landscape condition resulting from logging and related activities caused the magnitude of the disturbance wrought by the 1964 flood to be greater than it otherwise would have been. Grant (1986) found that streams draining logged basins in the Middle Fork Willamette basin were 4.5 times more likely than streams draining unlogged basins to exhibit riparian canopy opening detectable in aerial photographs as a result of the 1964 flood. He concluded that increased rates of landslides and debris flows associated with clearcuts and logging roads were responsible for increasing the frequency of riparian canopy opening in 4^{th} and 5^{th}-order streams in response to major floods.

What is responsible for the fact that some reaches seem to exhibit a cyclical pattern of disturbance and recovery (e.g., the lower Lookout Creek site) while others appear to have undergone a long-term shift toward a more dynamic response to flood disturbances (e.g., Lookout Creek at the McCrae Creek junction)? One likely explanation is the degree of topographic confinement of the channel. At the junction of Lookout and McCrae Creeks, the valley bottom is wide and relatively flat. Prior to the December 1964 flood, the channel was in some sense "biologically constrained" by the adjacent confer forest, but in a major flood with abundant logs and sediment the channel was able to move laterally by encroaching upon the low forested floodplain surfaces. At the LOL site, however, the channel is bordered by a high terrace on the east and by a forested floodplain or low terrace on the west bank that is high enough that even during major floods like those of 1964 and 1996 it is not subject to flow of sufficient depth or velocity to cause major disturbance of vegetation or scouring of new channels. Thus, this study supports the general notion (Grant and Swanson, 1995) that reaches unconstrained by valley sidewalls or valley floor landforms can be "opened up" by a catastrophic, debris-flow-augmented flood, effectively increasing the width of the active channel floodway, but topographically constrained reaches have boundaries that are more nearly fixed on time scales of decades to centuries.

In addition to topographic confinement, the potential for major restructuring also depends upon the location of a given reach of channel in the watershed with respect to the portion of the landscape susceptible to mass movements (Figure 9.1), and the stochastic spatial distribution of individual debris flows and other mass movement processes within this zone. The LOM site, for example, is bordered for much of its length by extensive conifer-forested floodplain areas on both banks, particularly the south bank, yet it did not experience catastrophic widening in response to either the 1964 or 1996 floods. This site is located near the upstream limit of the portion of Lookout Creek that has been documented to have received tributary debris flow inputs during the latter half of the 20th century (Figure 9.1). The relative absence of debris flow activity may explain why the channel at the LOM site has not encroached dramatically upon the adjacent forested surfaces despite the accessibility of these surfaces to floodwaters.

It was hypothesized that a major flood such as the December 1964 or February 1996 floods could decrease the reach-scale channel stability in the short term by causing changes that would simultaneously contribute to decreased channel resistance to erosion and increased erosive power by floods. Channel changes that would increase the erosive power of floods are those that would decrease hydraulic roughness, thereby increasing flow velocity (hence, also increasing the shear stress acting on the bed and banks) for a given discharge. Such changes include removal of riparian vegetation, removal of LWD (especially old-growth logs), straightening and simplification of channel morphology (e.g., a change from multiple low-flow channels to a single channel), and channel aggradation that results in burial of large boulders and/or a decrease in bed material particle size. Channel changes that would decrease channel resistance to erosion include disruption of the bed surface armor layer or pavement (Parker and Klingeman, 1992), removal of riparian vegetation whose roots bind together channel bar and bank sediments, and removal of bank-armoring logs (e.g., logs at XS 3, 4 and 5 at the LOL site, Figure 9.8[a]).

Although many of these types of channel changes occurred at the LOL site as a result of the 1996 flood, the data for 1997 and 1998 do not show any evidence of an increase in channel sensitivity to disturbance after 1996. The 1997 data provide a good test, because the maximum peak flow in Lookout Creek in that year was similar to the February 1986 flood in magnitude. The cross section response index score for the LOL site was nearly identical in 1986 and 1997 (Figure 10.14). Thus, despite the fact that the peak unit area discharge in Lookout Creek was slightly higher in 1997 than in 1986 (1.35 vs 1.23 $m^3/km^2/s$) and there were two other peak flows in 1997 that exceeded the mean annual peak discharge—one of which was nearly as large as the 1986 flood (Figure 10.1[b])—the cross section data suggest that the channel response was the same or lower in 1997 as in 1986.

11.5 Limitations of Cross Section Data

As a tool for monitoring flood-related channel changes in mountain streams, cross sections have significant limitations. "Noise" inherent in cross section measurements in coarse-bedded mountain streams—e.g., the large size of some individual particles relative to the channel dimensions and the common presence of LWD which interferes with profile surveys—limits the resolution of change detection, while the infrequent occurrence of geomorphically significant changes limit the number of "observations" of such events that can be obtained within a reasonable period. Moreover, cross sections alone only document limited aspects of channel response. They provide little information on changes in the structure of the longitudinal profile of the channel, which can be a key aspect of channel morphology and potential adjustment in steep, stepped channels (Grant et al., 1990; Grant and Mizuyama, 1991), and it is difficult to infer changes in channel plan form from cross section data alone. Many channel changes recorded by cross sections are related to LWD interaction with sediment, but cross sections by themselves do not provide much information on this interaction. Cross sections also are not very helpful in assessing flood-related disturbance of riparian vegetation, and they are poorly suited for monitoring channels that do not have well-defined, relatively fixed banks (i.e., avulsion-prone channels).

Implementation of a set of additional measurements at cross section sites might overcome many of these difficulties. Because of the lack of historical data, the cross section monitoring data analyzed in this study were of limited use for evaluating the effects of local channel characteristics at the scale of channel units or individual cross sections on the style, frequency or magnitude of channel response to peak flows. For example, channel unit types (*sensu* Grant et al., 1990) were not documented, nor were measurements of local low-flow water surface gradient, bed material particle size (prior to 1995), or LWD influence part of the data set. Since these local scale influences can vary over relatively short time scales and clearly have not been constant over the duration of the monitoring period, post-hoc measurements cannot be used to assess the influence of these local channel properties on historical channel response.

Measuring these local channel characteristics in conjunction with ongoing cross section monitoring would substantially increase the utility of the cross section data for assessing the importance of local vs. reach scale controls on channel response. Periodic re-mapping of channel plan form geometry would also substantially increase the ability to interpret cross section changes in terms of styles and patterns of channel response. This could be done following floods exceeding a specified magnitude—for example, floods with a recurrence interval of greater than 5 years.

12 Conclusions

12.1 Summary

Large scale restructuring of the channel occurs infrequently at the Lookout Creek and Mack Creek study sites, particularly the latter, but some degree of bed mobility occurs relatively frequently at each of the study sites. Flows which produce observable change in, on average, 25% of cross sections, representing significant bedload transport, have estimated recurrence intervals of between 1.7 and 3.0 years. Patchy reworking of significant portions of the channel bed at the Lookout and Mack Creek sites occurs during floods with estimated recurrence intervals in the range of approximately 3 to 6 years, which are capable of producing detectable change in approximately 50% of cross sections. Peak flows capable of major restructuring of the channel and adjacent riparian vegetation have an estimated recurrence interval of greater than 7 and less than 90 years in mainstem Lookout Creek and >25 years (perhaps much greater) in Mack Creek.

The cross section data also corroborate the expectation, based on recently published conceptual models (e.g., Montgomery and Buffington, 1997; Montgomery, 1999) that the frequency of bed mobility should be greater in mainstem channels than in lower order tributaries. Peak flows producing detectable change at 90% of cross sections—flows able to rework significant portions of the channel bed and cause significant channel adjustments—are estimated to occur approximately 3 times as frequently (approximately once every 7 years, on average) at the two 4th to 5th-order Lookout Creek sites as at the two 3rd-order Mack Creek sites (approximately every 23 years).

The results of this study also provide a means of assessing the likely impacts of increased peak flow magnitudes due land use practices such as logging and associated road construction (Jones and Grant, 1996; Jones, in press) on stream channels. For example, a 25% increase in peak flow magnitudes, assuming that flood peaks of all sizes are increased by the same proportion, is predicted to increase the frequency of events capable of causing detectable change at 90% of cross sections to increase by three-quarters in Lookout Creek and by nearly a factor of 3 in Mack Creek. Even if the magnitudes of the largest floods are not affected by land use impacts, a 25% increase in the magnitude of peak flows up to the size that mobilize a significant portion of streambed sediments (50% cross section response) could cause the frequency of such events to increase from about once every 3 years to about once every 2 years in Lookout Creek and from once every 4 to 6 years to about once every 2 to 3 years in Mack Creek.

Steep, 1^{st} to 2^{nd}-order tributaries (≤1 km^2 drainage area) and 4^{th} to 5^{th}-order mainstem channels (~10 to 100 km^2 drainage area) in the Western Cascades exhibit distinctly different styles and spatial patterns of channel response to major floods as a result of the different disturbance mechanisms affecting them. Low-order tributaries exhibit an essentially a binary response that is patchy at the landscape scale—entire channels either are severely disturbed by debris flows, which completely rework the valley bottom and obliterate riparian vegetation, or they experience only very limited and patchy disturbance of the channel bed and riparian vegetation by floods in the absence of debris flows.

Mainstem channels, on the other hand, are subject to a more continuous spectrum of disturbance intensity during major floods, such as the December 1964 and February 1996 floods, ranging from moderate to severe. As a result, they exhibit channel and riparian responses that are patchy at the reach and finer scales. Pulse inputs of large wood and sediment—principally from debris flows but also from wood jam failures, riparian landslides, and slumps at earthflow toes—control reach scale disturbance intensity in combination with reach-scale channel characteristics such as the degree of lateral channel constraint by bedrock, hillslopes, or valley floor landforms. Channel changes are principally controlled by the degree of channel constraint, the availability of sediment, and the interaction between wood and sediment. The largest changes in channel configuration occur in unconstrained reaches where abundant sediment and wood are supplied from upstream debris flow inputs or other sources. Constrained reaches efficiently route sediment and wood downstream; but constraint limits lateral channel movement while armored beds limit channel scour and high shear stresses limit opportunity for deposition. These factors combine to limit the potential for channel change within constrained reaches.

Intermediate size (3^{rd}-order, 1-10 km^2) channels are generally too large and insufficiently steep to be scoured by debris flows, but—short of a truly catastrophic flood—too small for strictly fluvial flood disturbances to completely restructure the channel or reset vegetated riparian surfaces as in mainstem channels. Flood surges associated with debris jam failure (Johnson et al., in press) may be one mechanism by which such changes can occur in these channels. In 3^{rd}-order Mack Creek, the February 1996 flood reworked substantial portions of the streambed, but caused only limited damage to riparian vegetation and apparently did not fundamentally restructure the channel (e.g., boulder cascade or step-pool sequences). While floods with a 50 to 100+ year recurrence interval (e.g., the 1964 and 1996 floods) are capable of thoroughly restructuring the channel and reworking many vegetated riparian surfaces in mainstem Lookout Creek, it is unclear what magnitude of flood would be required to achieve the same level of disturbance in Mack Creek.

LWD plays a key role in moderating or enhancing channel and riparian response to floods. In 1^{st} to 3^{rd}-order streams, LWD is generally very stable and constitutes a major structural element of the channel. Stable LWD increases may limit channel scour at the reach scale during large floods by dissipating flow energy and providing stable sediment deposition and storage sites. In larger streams, moving individual pieces or batches of LWD are a major agent of riparian disturbance (i.e., toppling and battering of riparian trees), while creation or collapse of LWD jams can lead to reach scale channel aggradation or degradation, respectively. Large logs also play an important role in lateral switching of the main channel thalweg in unconstrained mainstem reaches where multiple active and inactive channels are often present.

Major floods can extensively rework the channel and adjacent vegetated surfaces in 4^{th} to 5^{th}-order mountain streams, initiating a cycle of disturbance and recovery. Much LWD previously stored in channels is flushed downstream or deposited on streambanks or floodplains during these events, and channel structure may be considerably simplified. In the aftermath of such events, channel complexity gradually recovers over time as new trees fall into the channel, riparian vegetation becomes reestablished on new or reworked surfaces, and the channel adjusts to these changes and redistributes the sediment deposited by the flood.

Major floods can also significantly alter channel characteristics in ways that can affect channel response to future floods. For example, floods can disrupt the surface armor layer that commonly develops on coarse-bedded, infrequently mobile streams, and can reduce channel roughness and hence flow resistance by removing LWD and riparian vegetation. This study found no evidence of a change in channel response to peak flows at four cross section sites in the first two years following the February 1996 flood. The December 1964 flood, however, led to dramatic widening of channels in many unconstrained reaches bordered by mature or old-growth conifer forest. By increasing the mobility of LWD and the potential for lateral shifts in channel position, such changes can leave a legacy of fundamentally altered dynamics of channel and riparian disturbance that may persist for decades or longer.

12.2 Future Research

An hydraulic analysis would provide a means of linking the observed cross section changes with predictions based on flow competence and sediment transport relationships and observations in other watersheds. For example, it would be useful to know what level of observed cross section response corresponds to flows predicted to mobilize the D_{50} or D_{84} particle size fractions, which would provide a means of comparing the results of this study with laboratory and field based studies of incipient motion in other stream channels and with flow competence based analyses of stream channel stability. Initial attempts at such an approach in this study encountered difficulties producing reasonable results due to abrupt changes in cross sectional area between adjacent cross sections. In addition, poor constraint on the relationship between discharge and flow stage at the cross sections and how this relationship may have changed over the monitoring period imposes limitations on the utility of hydraulic calculations based on the historical cross section data. Hydraulic calculations for large floods such as the February 1996 flood are further complicated by the unknown relationship between pre- and post-flood channel configurations and the configuration at the time of the flood peak, as well as by out-of-bank flows. Such analyses also ignore the effects of large pulse inputs of sediment and LWD by debris flows, which, as this study showed, have a major impact on channel response. Measurement of flood stream stage at the cross section locations over a range of discharges to establish empirical stage-discharge relationships could remove much of the guesswork from hydraulic analyses based on the cross section data.

A potentially fruitful area for future long-term studies would be to examine the effects of widening of the channel and the forest canopy gap in unconstrained mainstem reaches during major floods on the dynamics of subsequent channel and riparian disturbance at a time scale of years to decades. The February 1996 flood may have created an opportunity to pursue such a study. The lack of aerial photographic coverage prior to the 1950s precludes the use of aerial photography to characterize channel and riparian dynamics prior to the 1964 flood for comparison with post-flood dynamics. However, by selecting study reaches that were not opened up by the 1964 flood but were opened up by the 1996 flood, it should be possible to use historical aerial photos and ongoing aerial photographic and field-based monitoring to compare pre- and post-disturbance channel dynamics. A comparative analysis between such sites and sites that were opened up by the 1964 flood could also shed light on questions such as what are the key land use factors (and their interaction with natural landscape characteristics) that have the greatest potential long-term impact on channel and riparian disturbance.

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Appendices

Appendix A

Summary of Particle Size Data for Mack Creek Cross Sections

Table A.1. Bed material particle size summary statistics for Mack Creek: (a) old-growth site (MAC), (b) clearcut site (MCC)

(a) old-growth site (MAC)

Cross	1995 Survey				1996 Survey				1997 Survey			
Section No.	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size
1	329	97	36	102	577	175	23	102	345	90	28	100
2	427	108	31	100	540	121	31	102	648	189	43	100
3	152	35	8	102	136	27	7	102	222	54	11	100
4	226	75	21	100	264	61	15	102	273	78	24	100
5	558	189	30	100	494	95	19	102	803	211	62	100
6	225	30	12	100	201	78	15	102	316	100	29	100
7	234	92	11	100	184	64	17	102	250	80	14	100
8	387	101	24	100	297	90	30	102	462	145	25	100
9	495	97	20	100	492	79	33	102	453	100	35	98
10	307	113	22	100	84	35	15	102	190	72	21	100
11	209	52	18	97	199	55	20	102	300	90	20	100
12	105	36	13	99	251	61	16	102	400	81	10	100
Avg/Sum	305	85	20	1200	310	78	20	1224	388	107	27	1198
C.V.	0.456	0.521	0.426		0.549	0.511	0.384		0.468	0.453	0.553	

(a) clearcut site (MCC)

Cross	1995 Survey				1996 Survey				1997 Survey			
Section No.	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size	D_{84} (mm)	D_{50} (mm)	D_{16} (mm)	Sample Size
101	158	47	11	100	433	118	26	102	321	110	24	100
102	315	99	21	100	306	83	19	102	401	81	18	100
103	312	100	20	100	388	75	17	102	342	84	20	100
104	152	60	15	100	418	126	43	102	505	142	60	100
105	223	71	9	100	324	84	28	102	431	106	21	100
106	333	69	12	100	418	122	30	102	400	168	29	100
107	315	63	15	100	557	68	12	102	734	272	31	100
108	219	68	14	100	478	132	24	102	550	190	36	99
109	214	54	12	100	353	80	22	102	303	87	35	100
110	160	29	10	100	458	129	26	102	444	148	27	100
111	238	60	10	100	395	132	23	102	420	120	24	98
112	192	83	29	100	318	89	20	102	382	101	30	100
113	159	36	14	100	403	92	17	102	572	150	25	100
114	121	34	10	100	324	83	15	102	280	93	42	100
115				0	462	110	23	102	490	150	19	100
117	133	40	18	100	415	129	20	102	581	170	28	100
118	257	74	12	100	514	93	14	102	439	149	30	100
119	432	118	24	100	382	96	19	102	363	100	35	99
120	272	52	17	100	378	57	14	102	333	96	29	100
Avg/Sum	233	64	15	1800	407	100	22	1938	436	132	30	1896
C.V.	0.359	0.378	0.358		0.166	0.240	0.332		0.262	0.357	0.327	

Appendix B

Filtered Cross Section Profile Plots

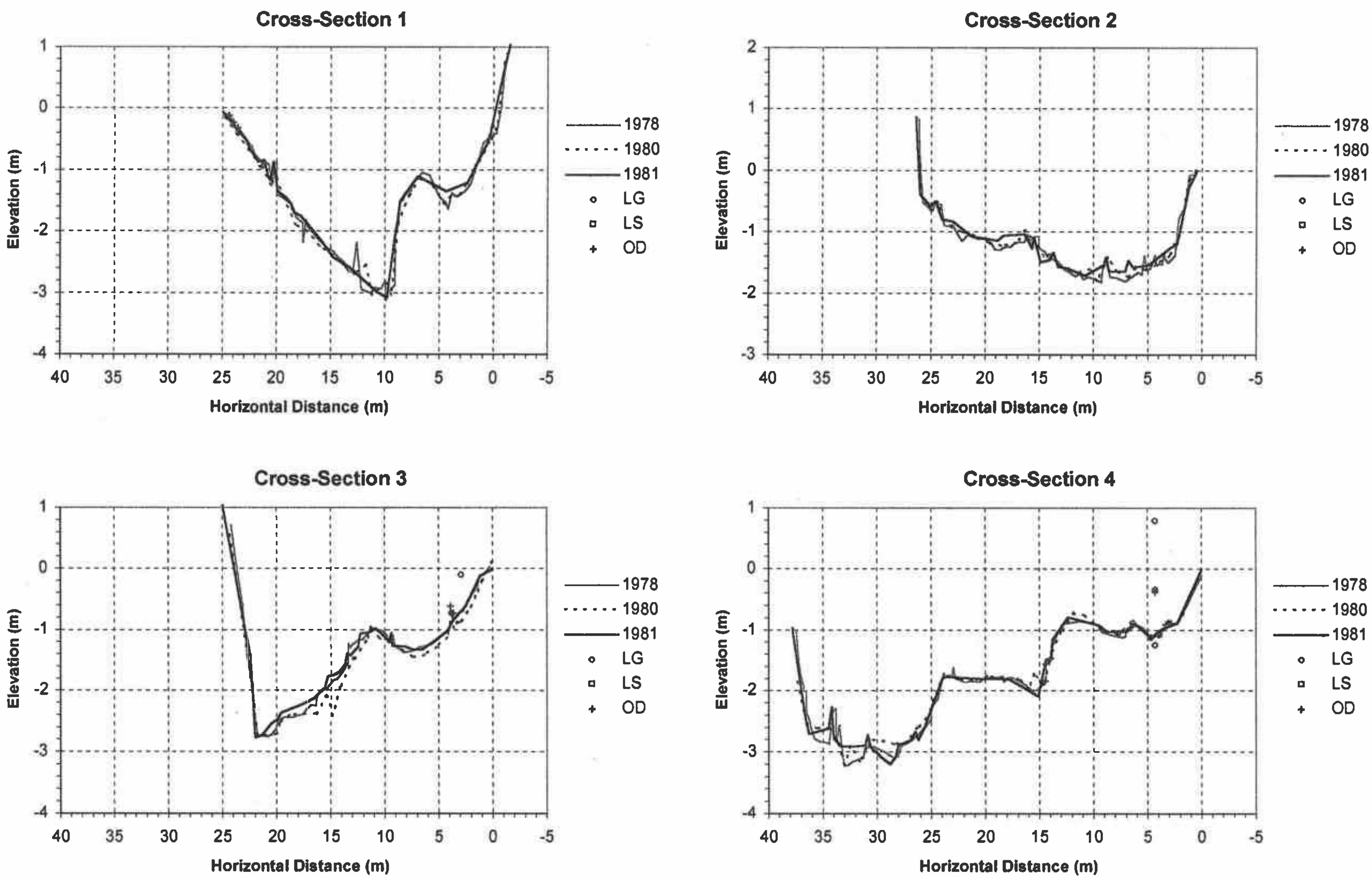


Figure B.1. Filtered cross section profile plots for lower Lookout Creek (LOL) site, 1978-81.

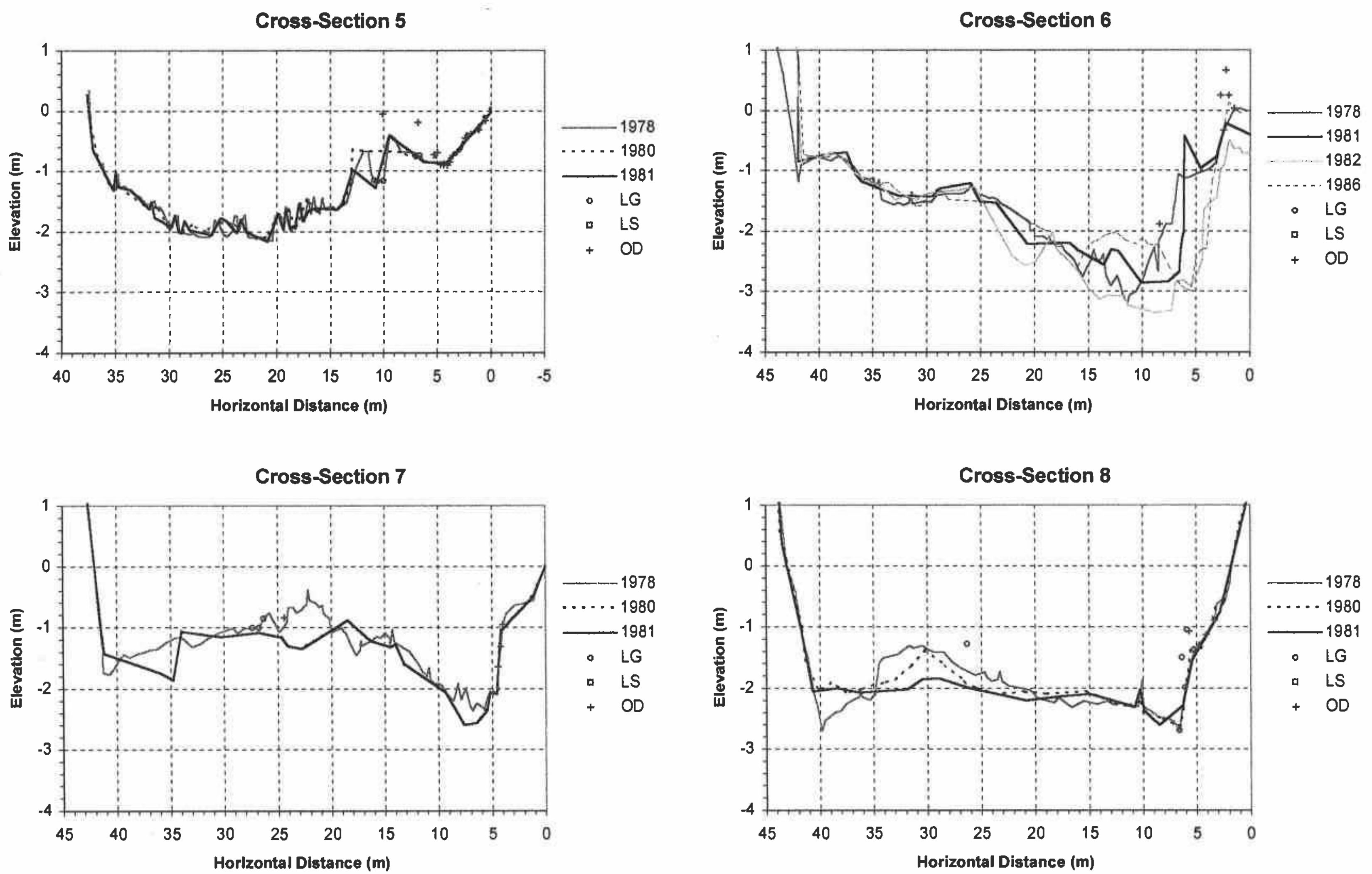


Figure B.1. (continued)

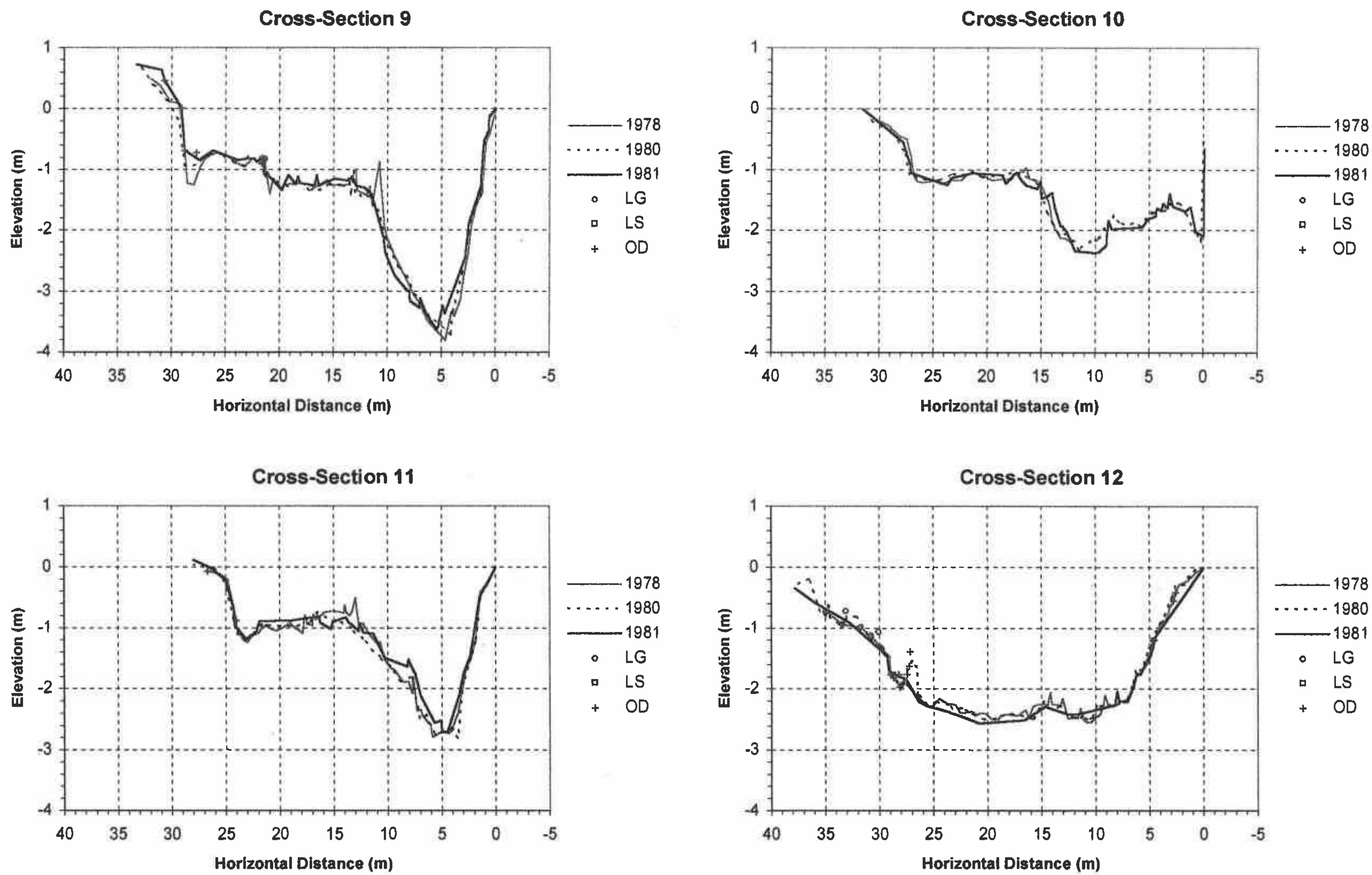
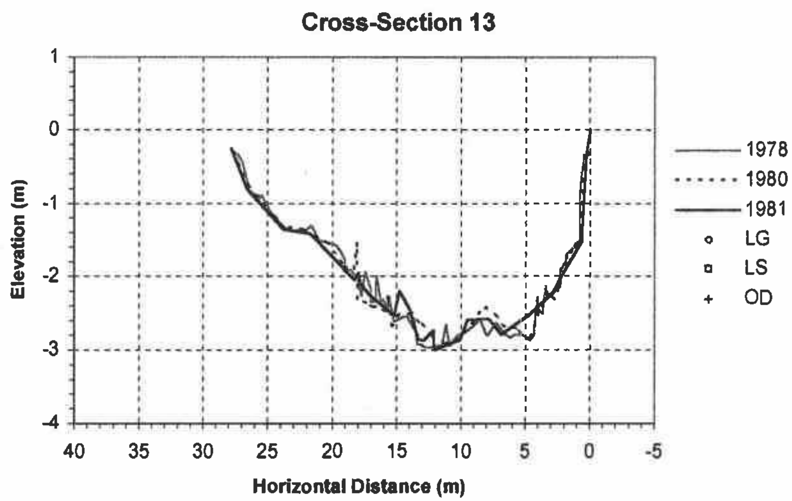


Figure B.1. (continued)



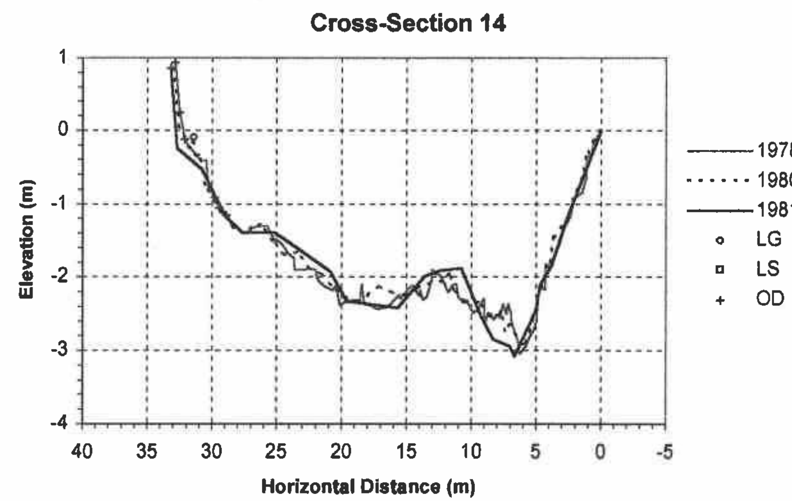


Figure B.1. (continued)

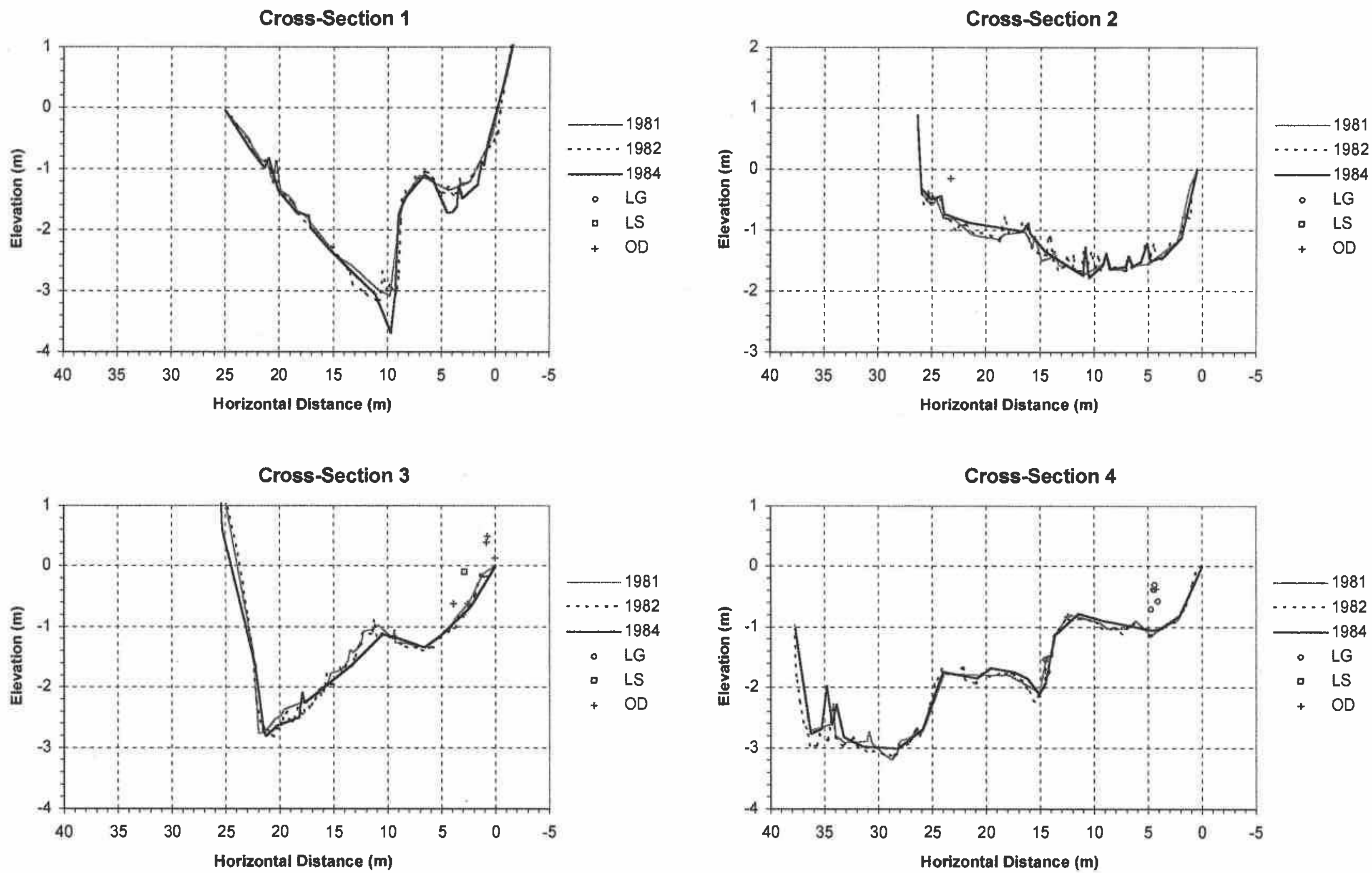


Figure B.2. Filtered cross section profile plots for lower Lookout Creek (LOL) site, 1981-84.

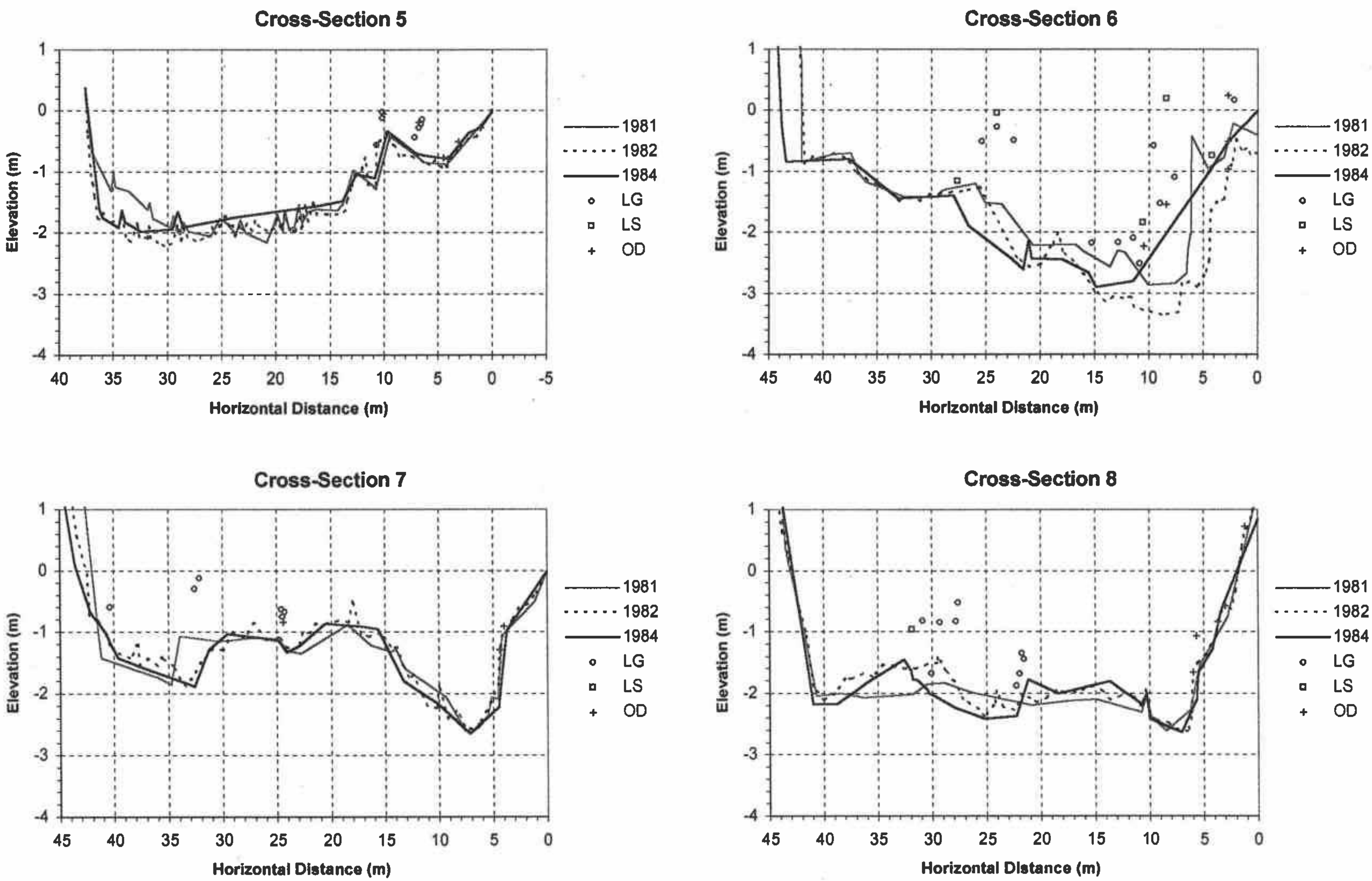


Figure B.2. (continued)

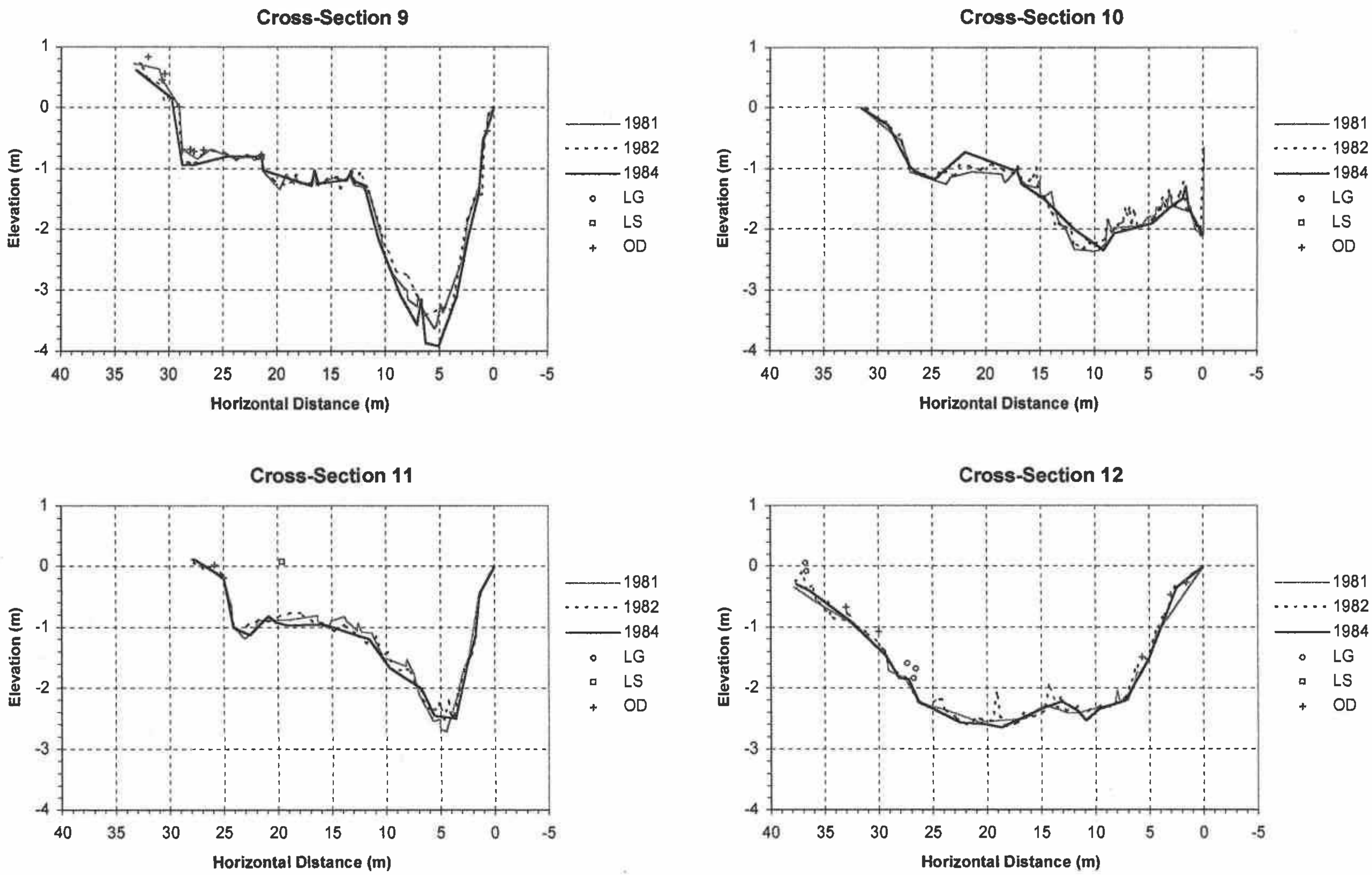


Figure B.2. (continued)

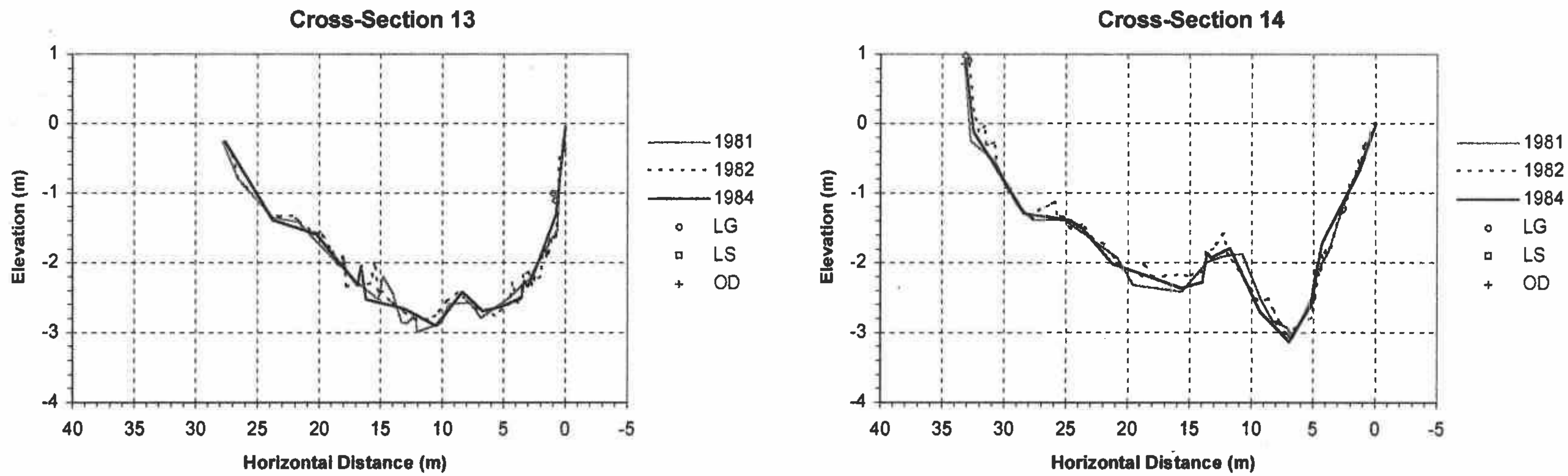


Figure B.2. (continued)

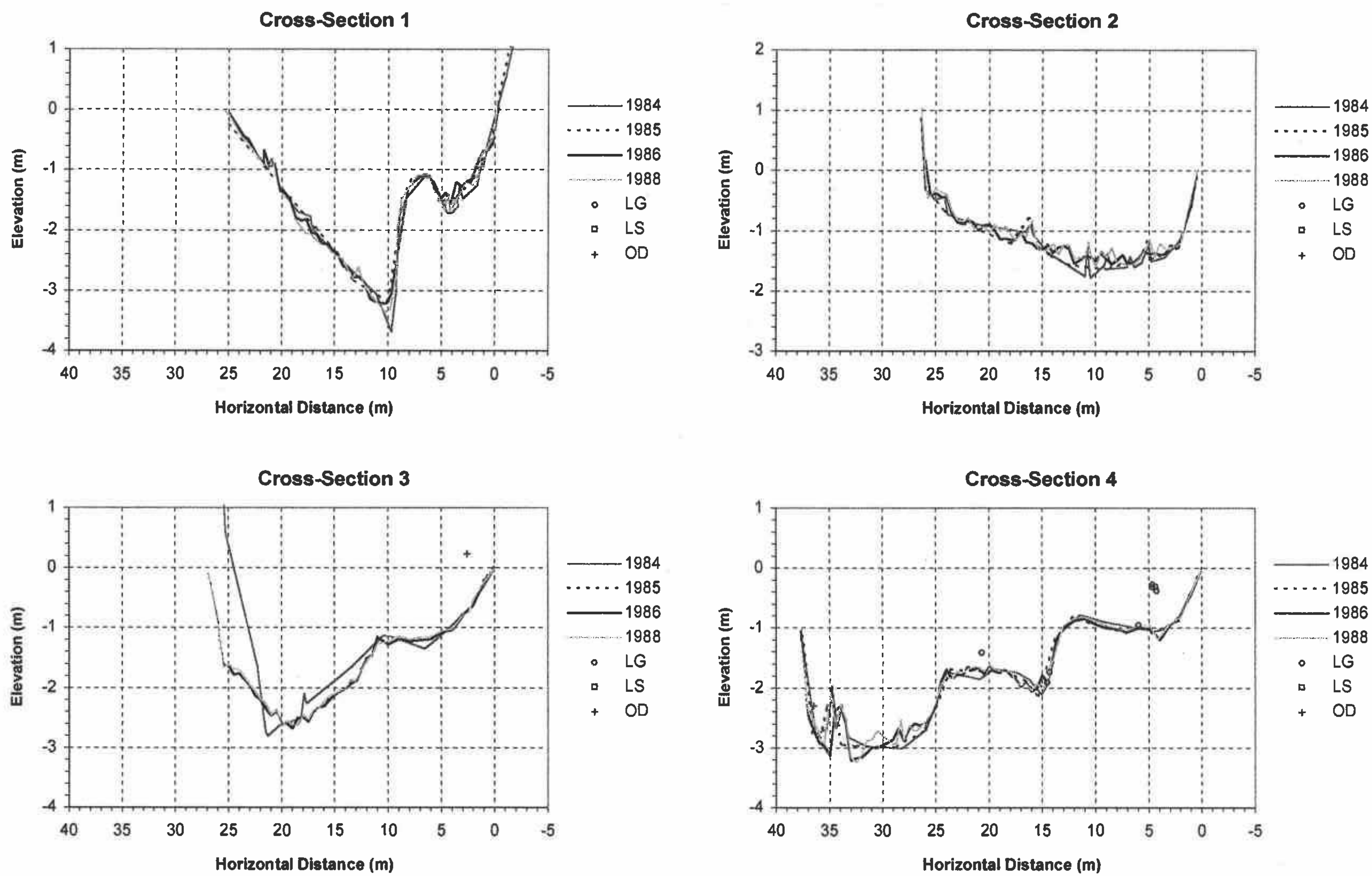


Figure B.3. Filtered cross section profile plots for lower Lookout Creek (LOL) site, 1984-88.

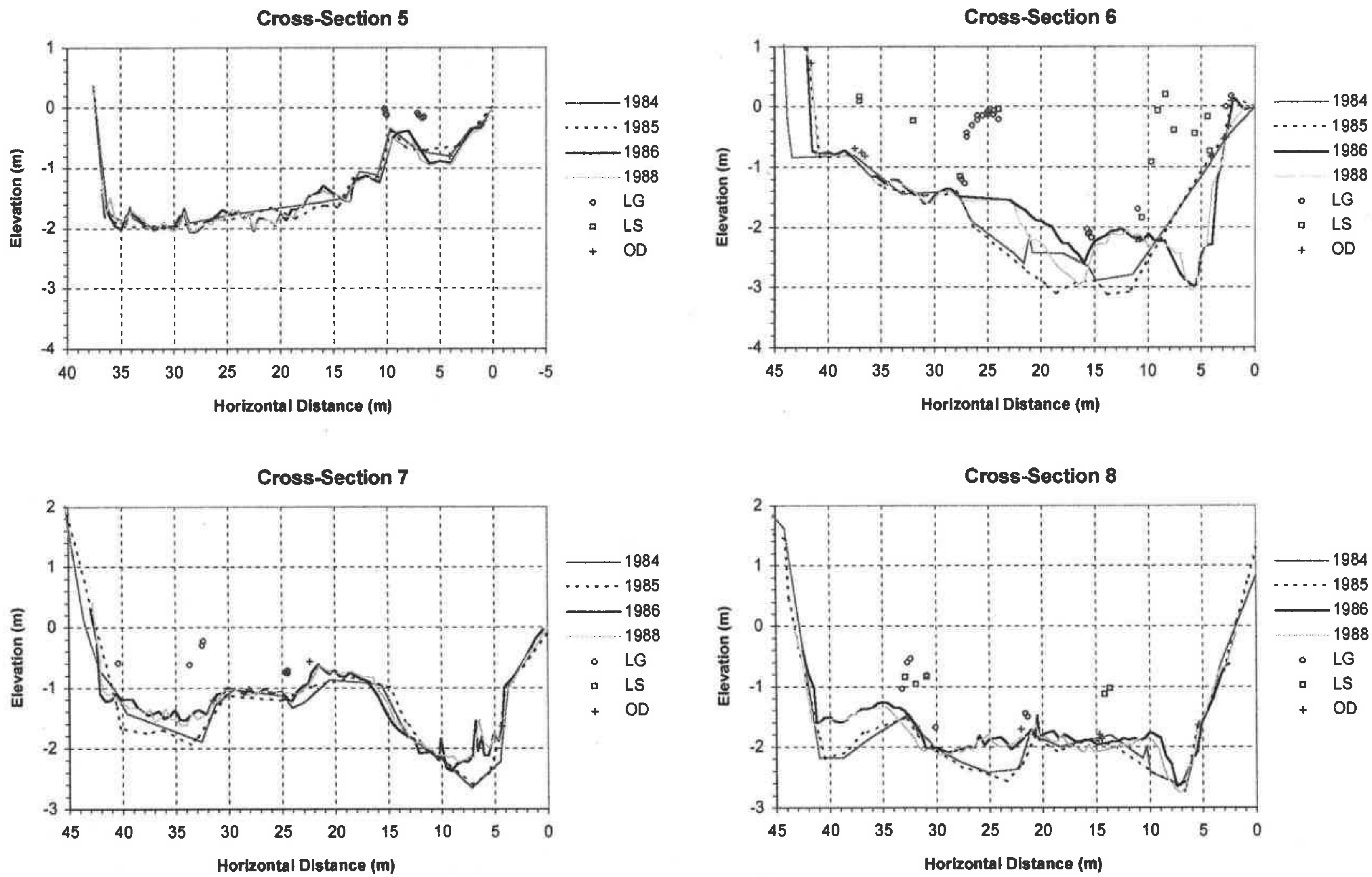


Figure B.3. (continued)

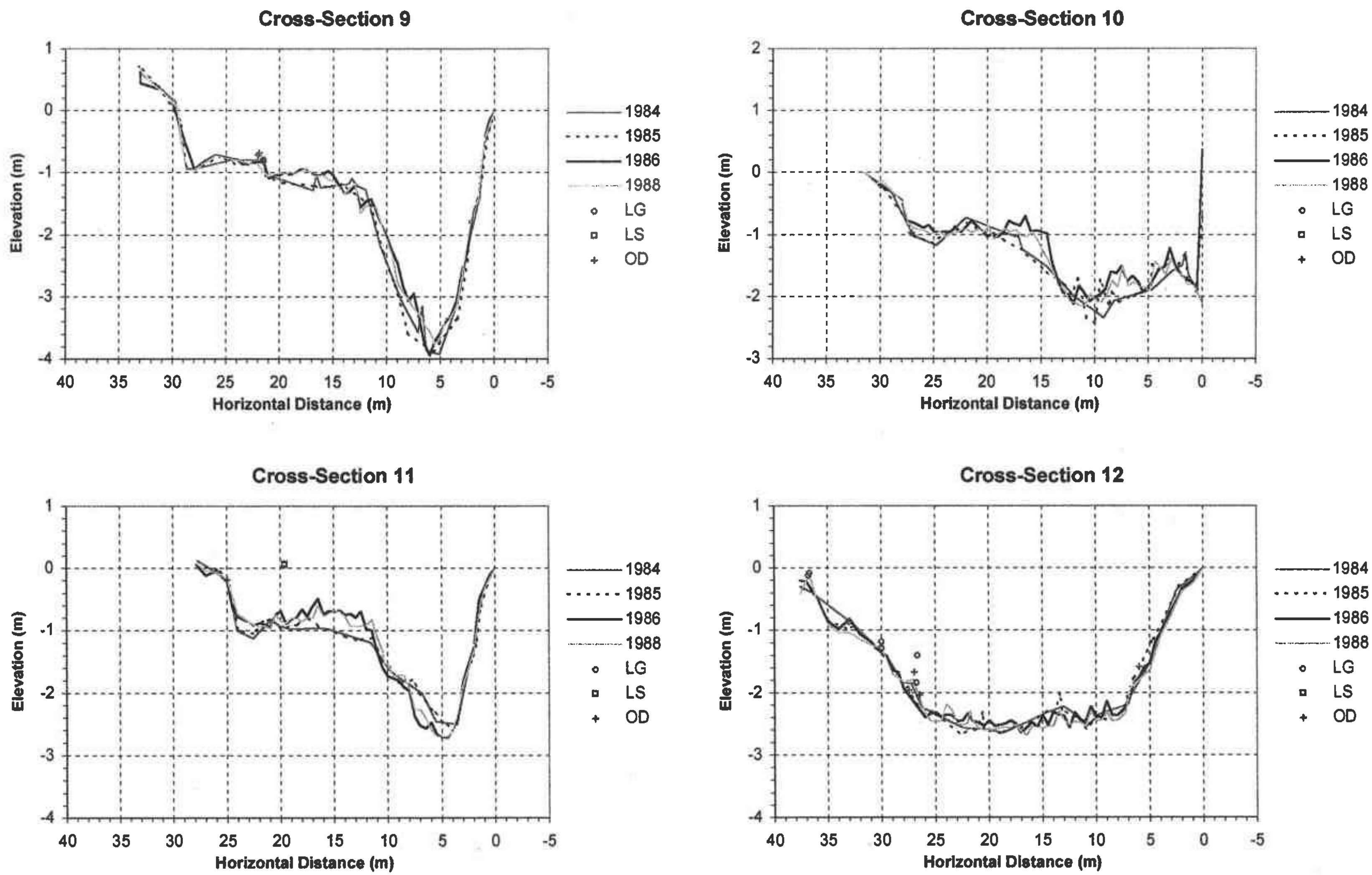
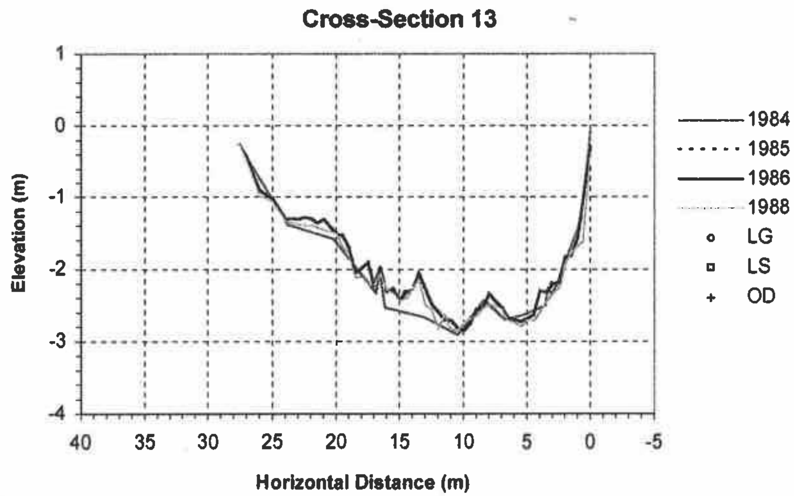


Figure B.3. (continued)



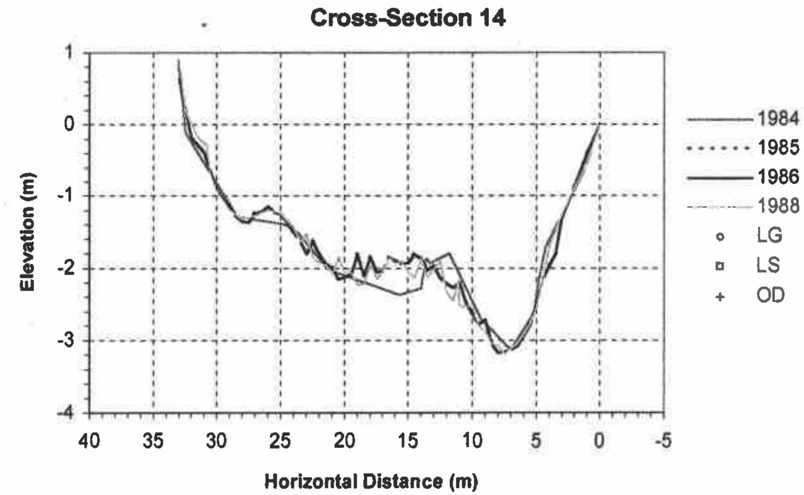


Figure B.3. (continued)

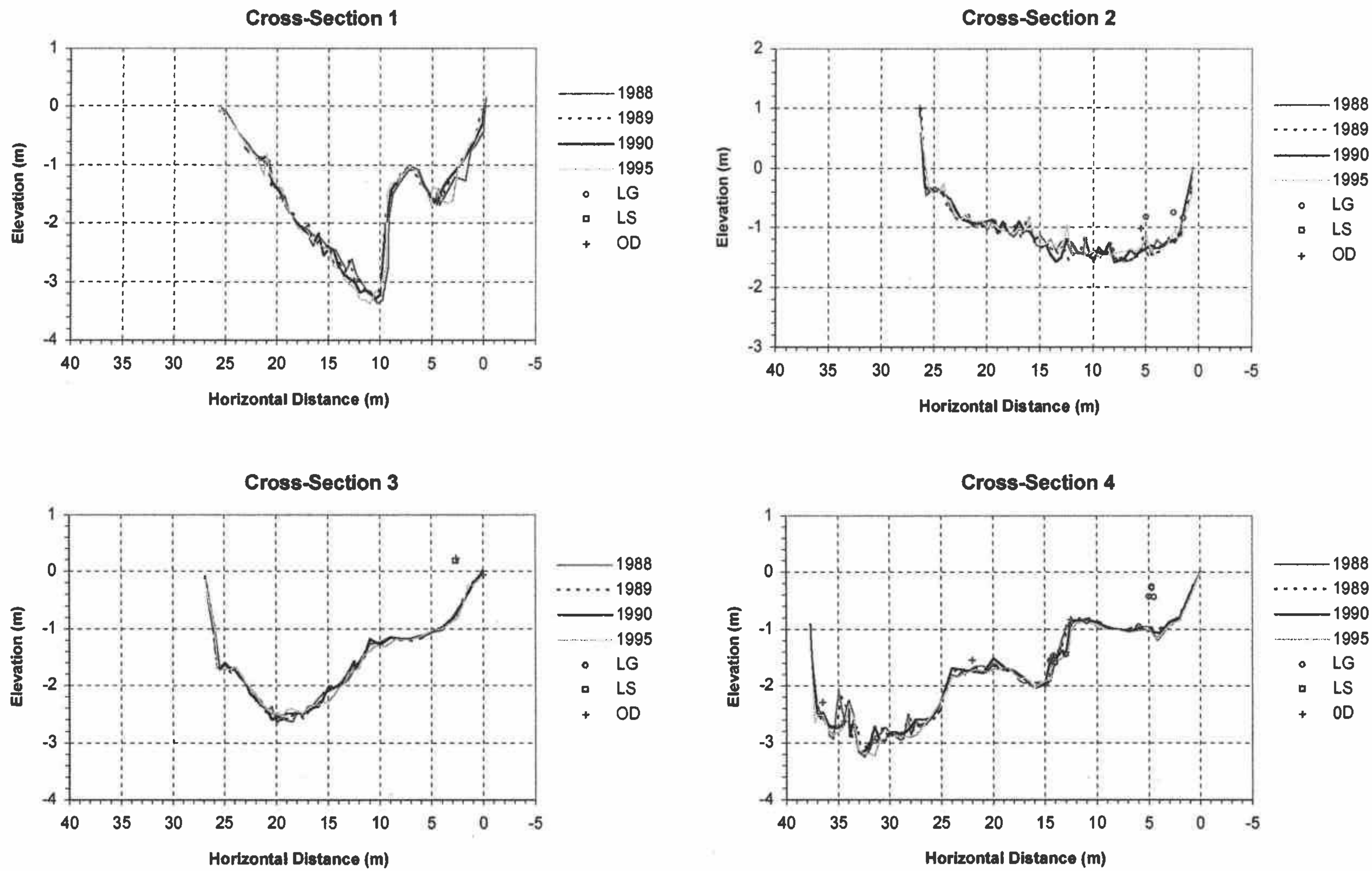
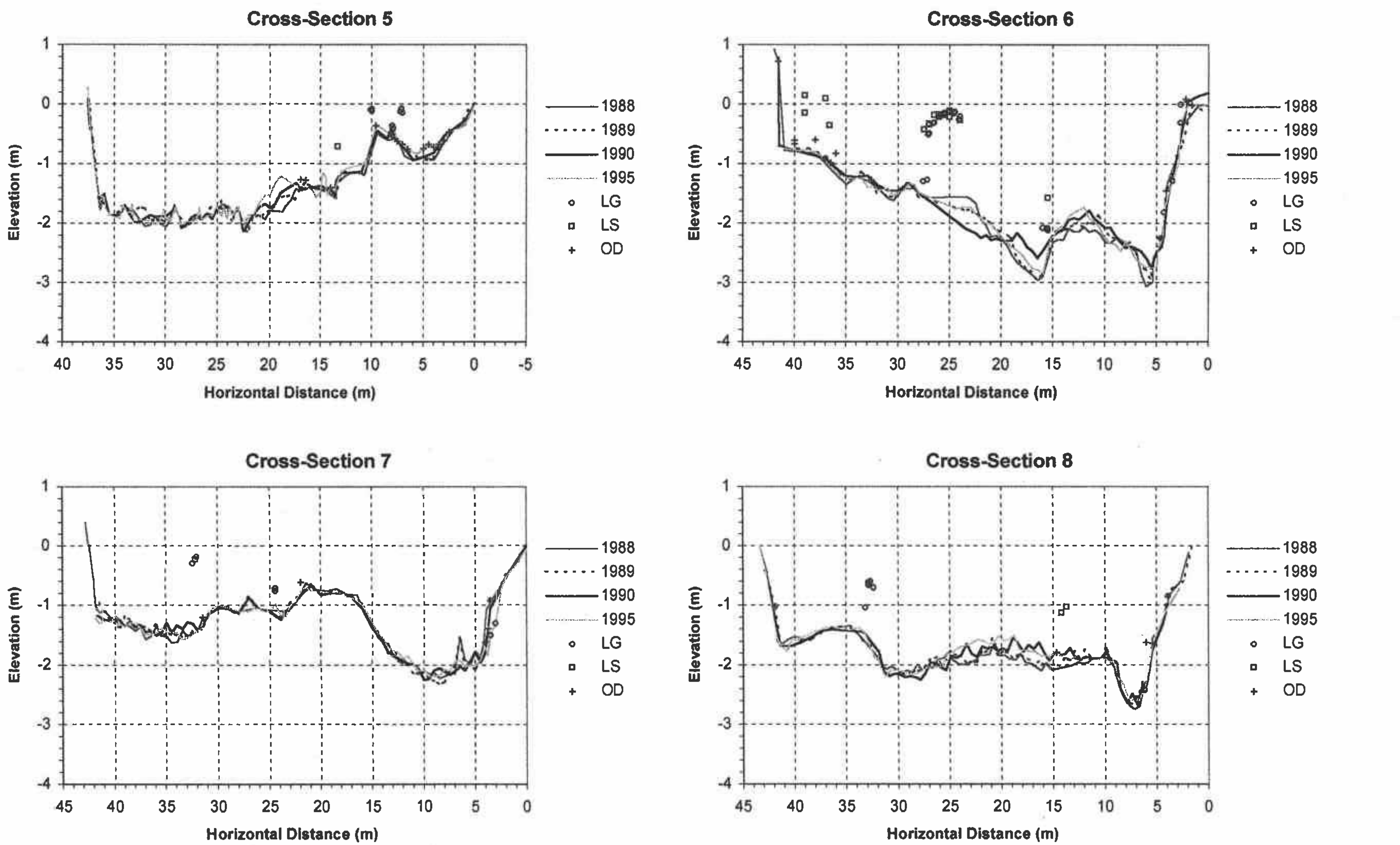


Figure B.4. Filtered cross section profile plots for lower Lookout Creek (LOL) site, 1988-95.



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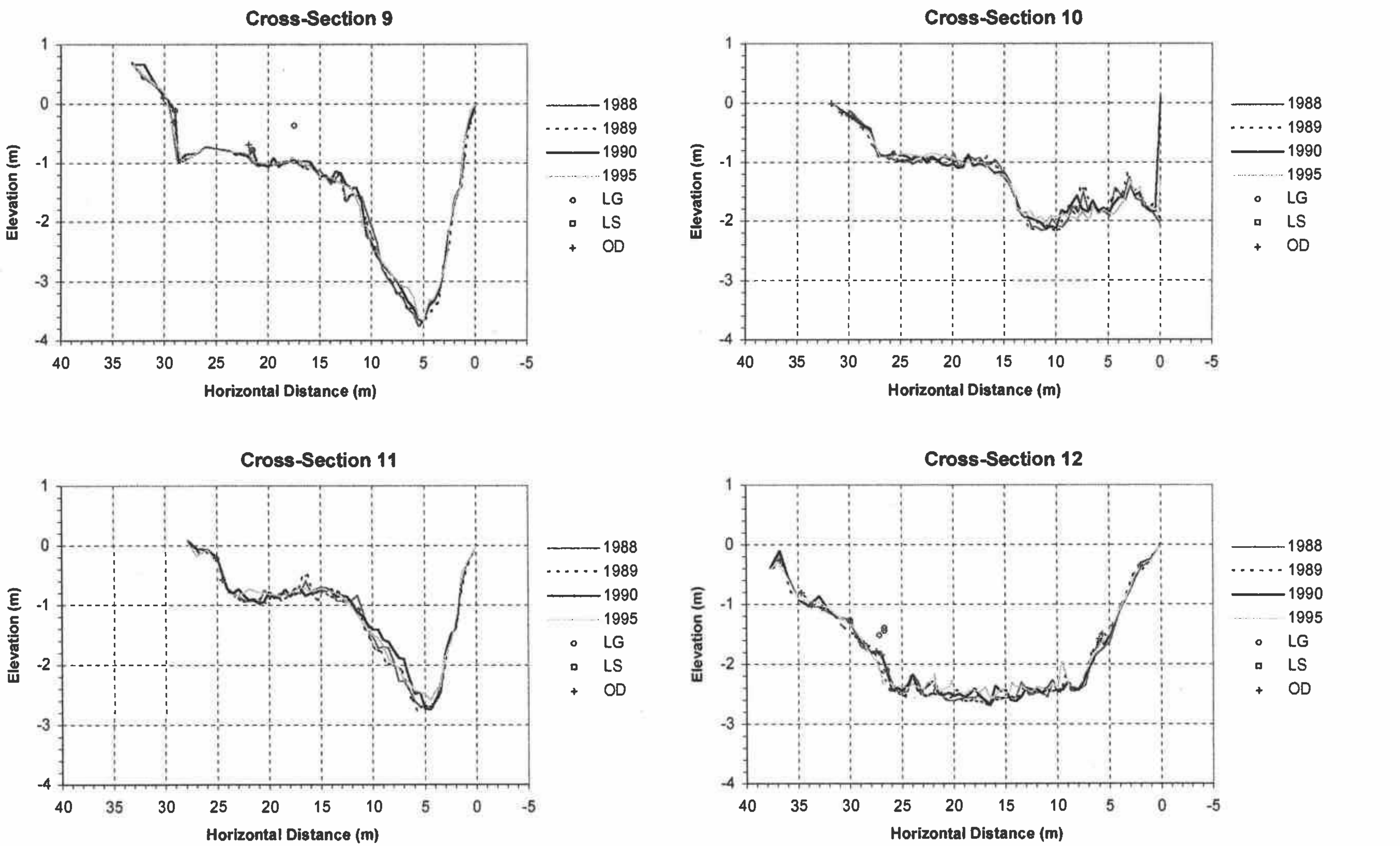
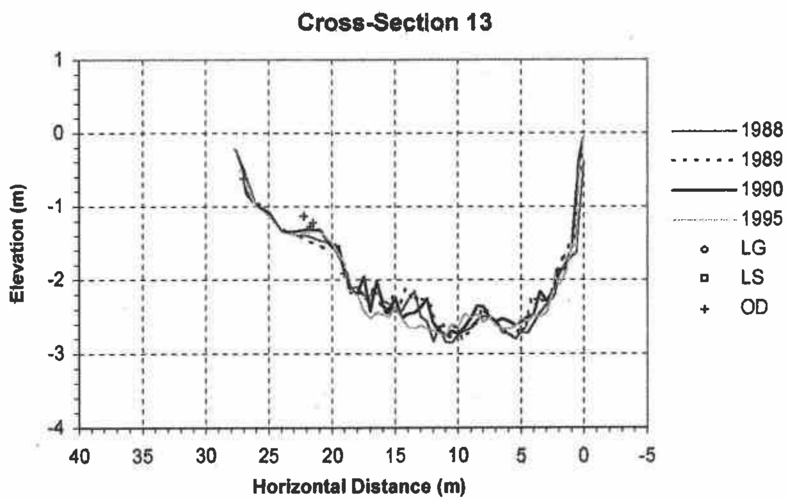
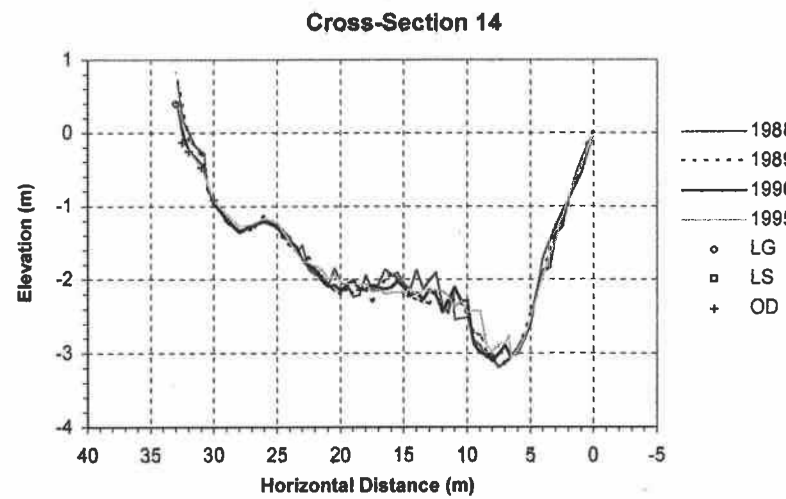


Figure B.4. (continued)





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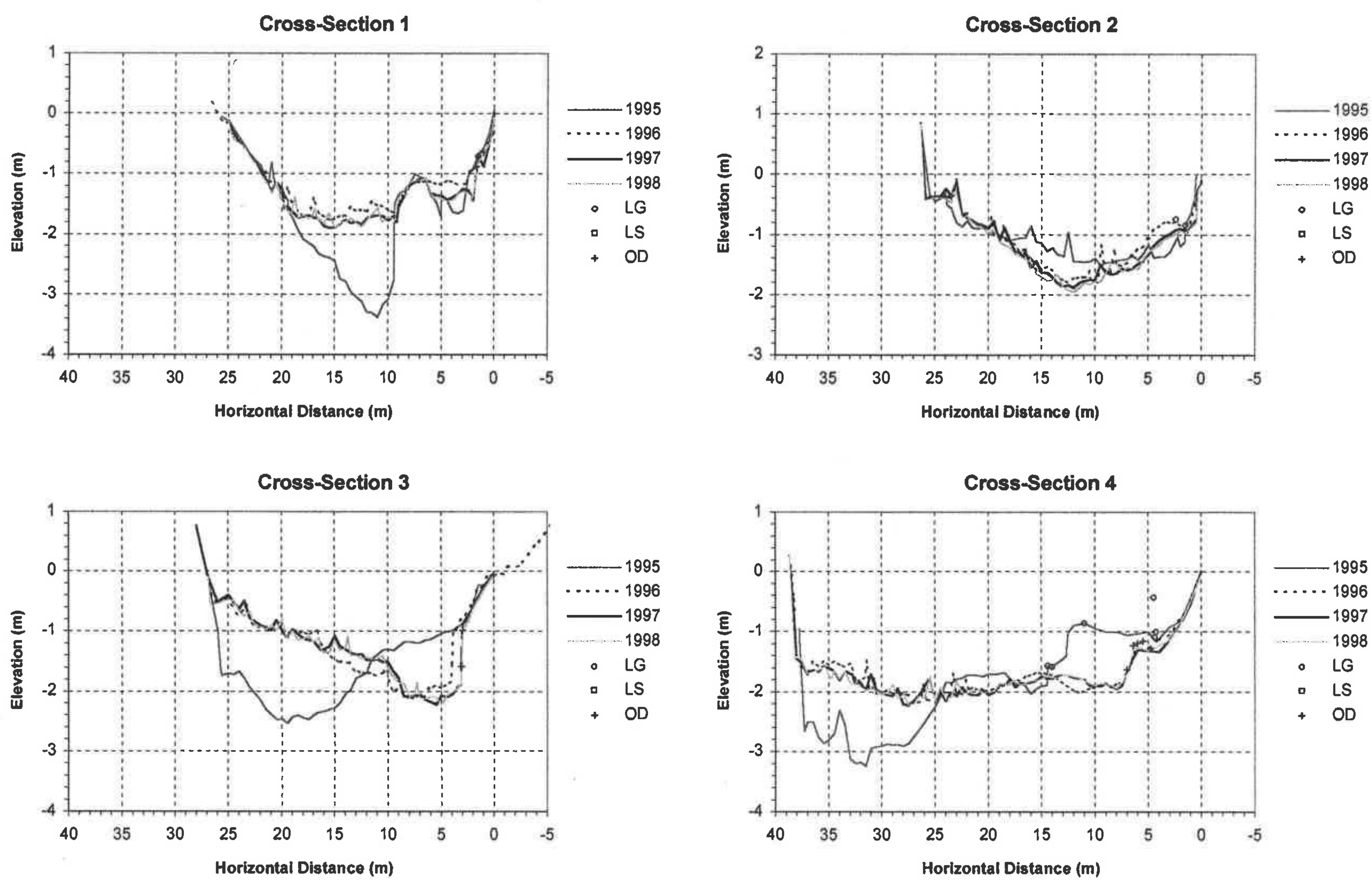


Figure B.5. Filtered cross section profile plots for lower Lookout Creek (LOL) site, 1995-98.

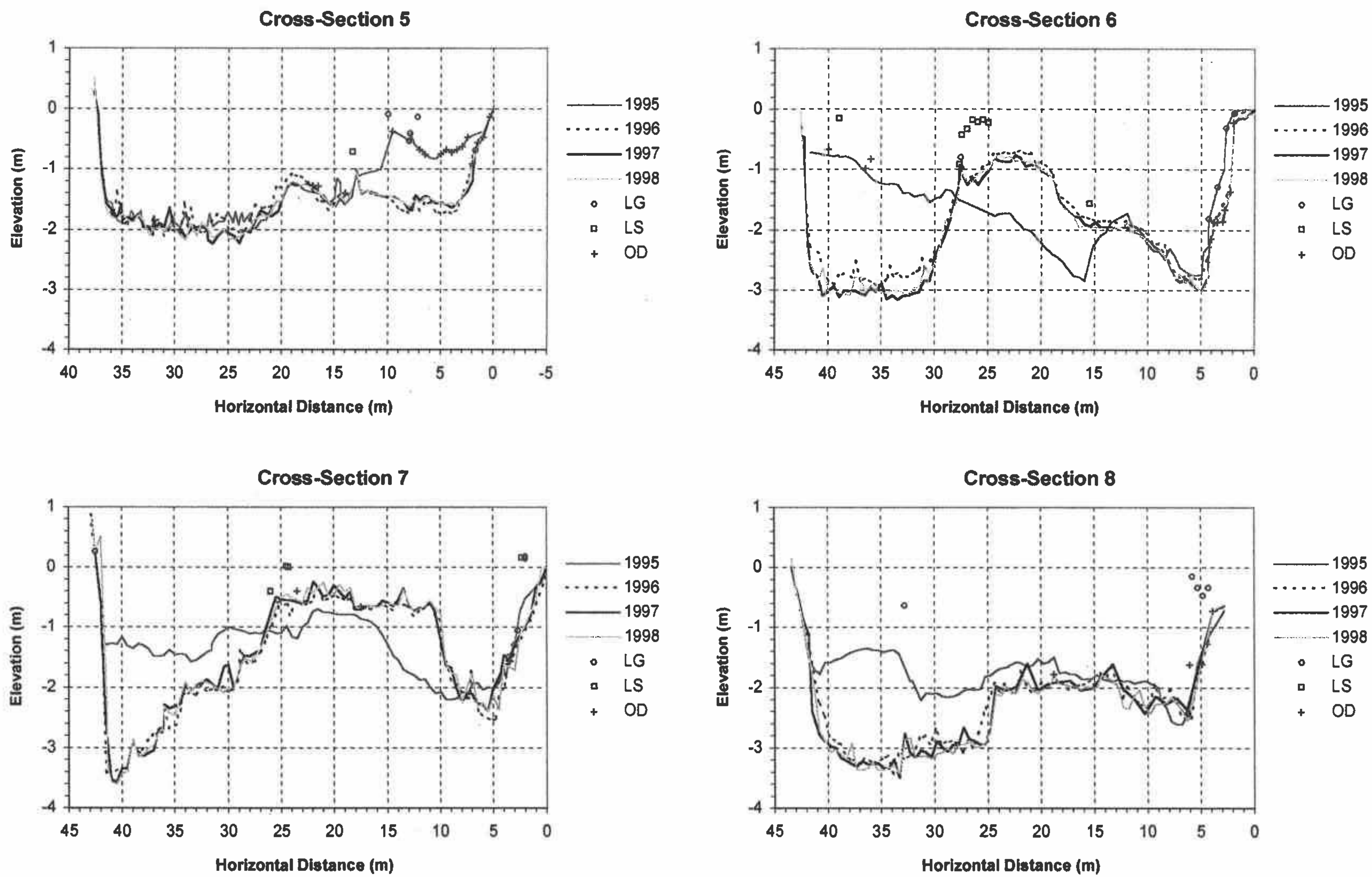
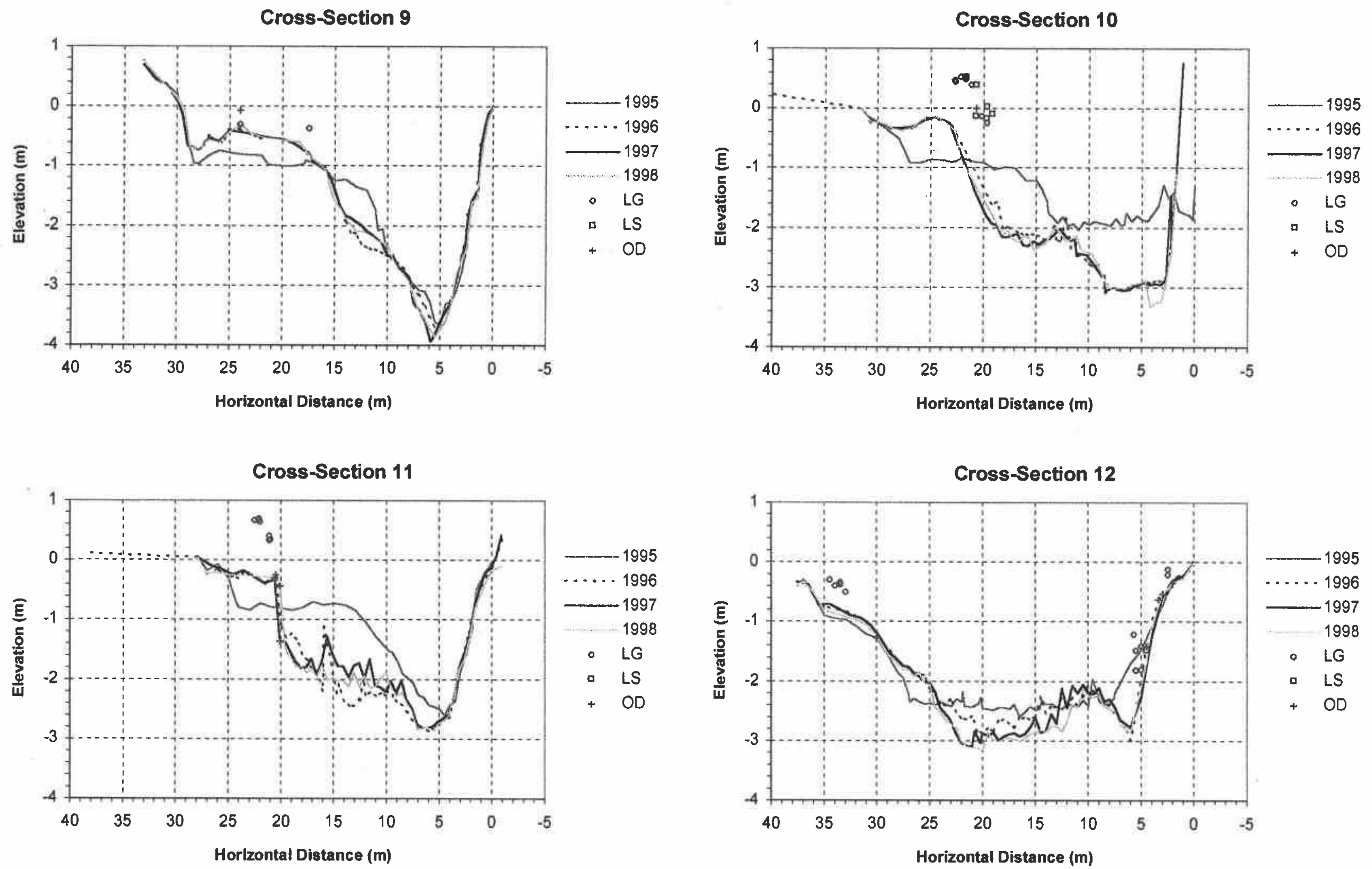


Figure B.5. (continued)



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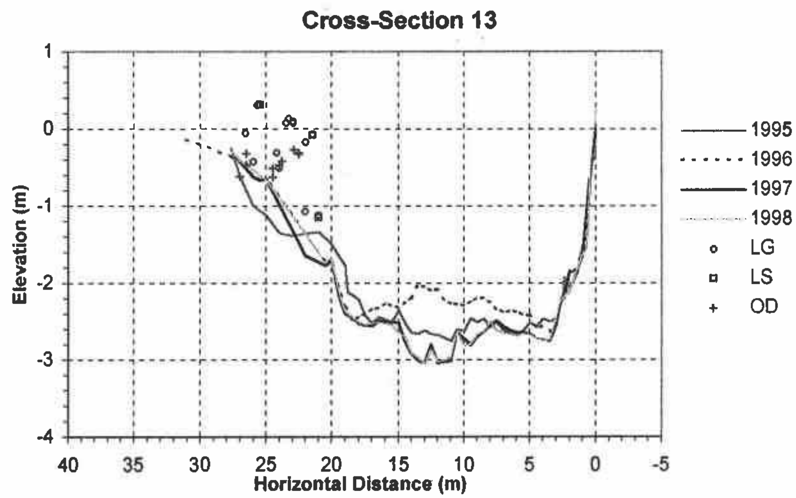

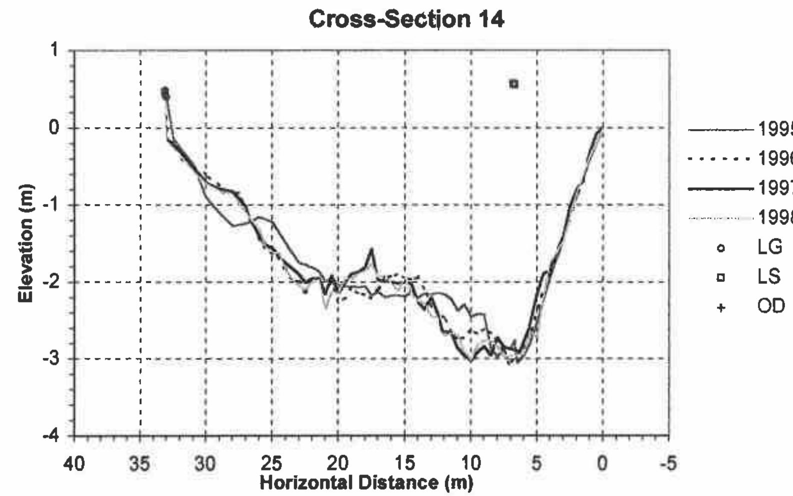

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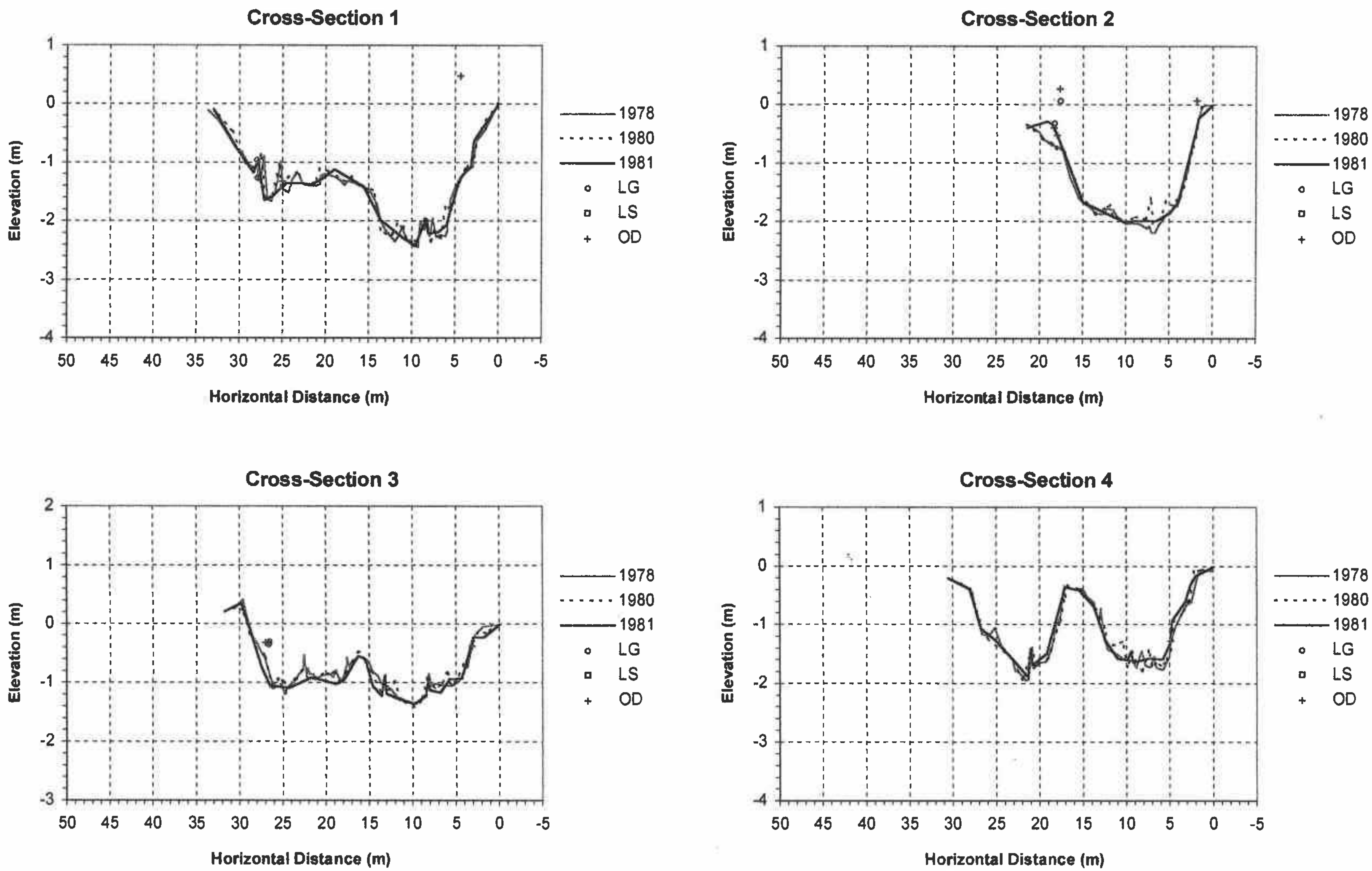
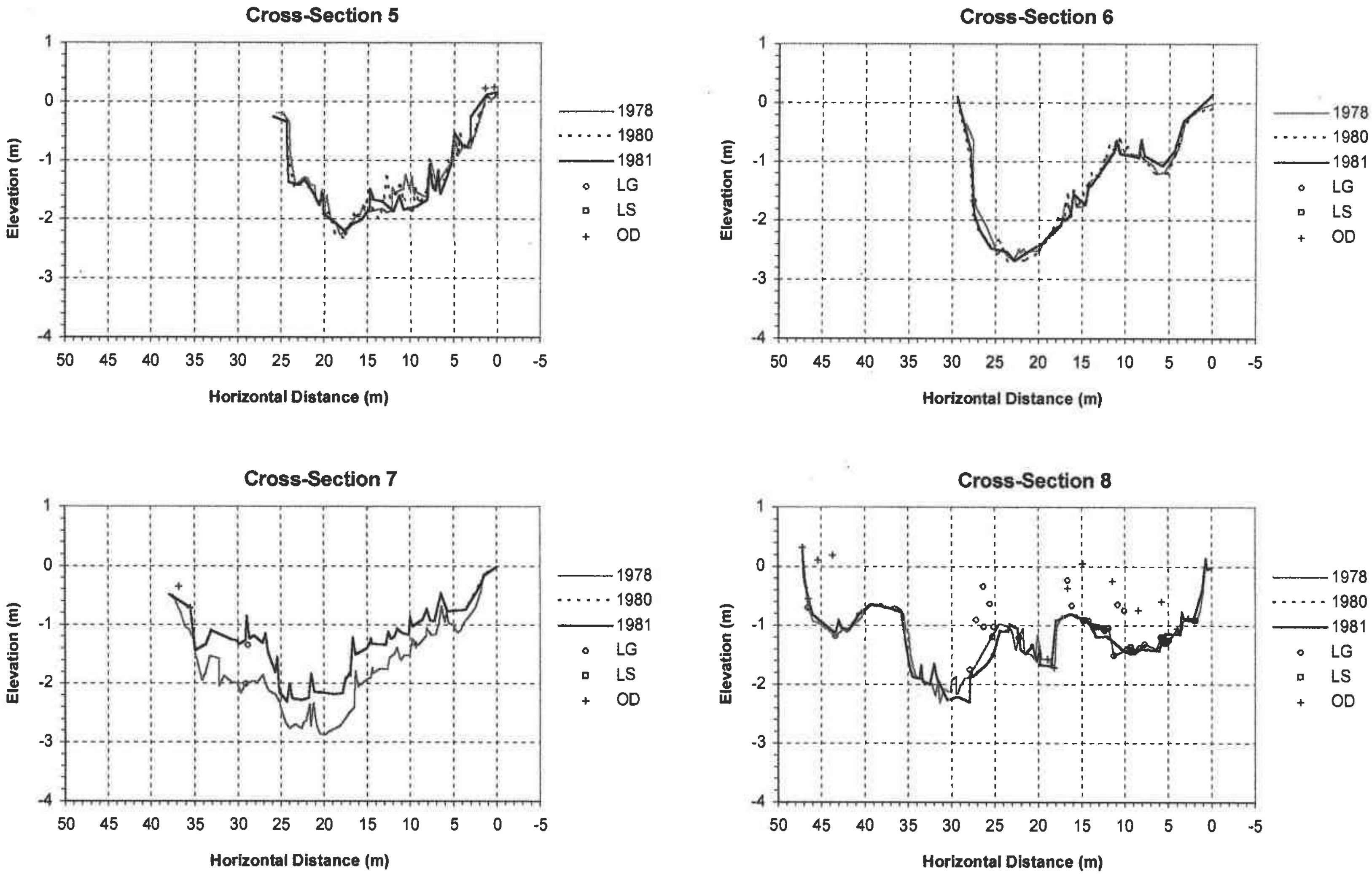


Figure B.6. Filtered cross section profile plots for middle Lookout Creek (LOM) site, 1978-81.



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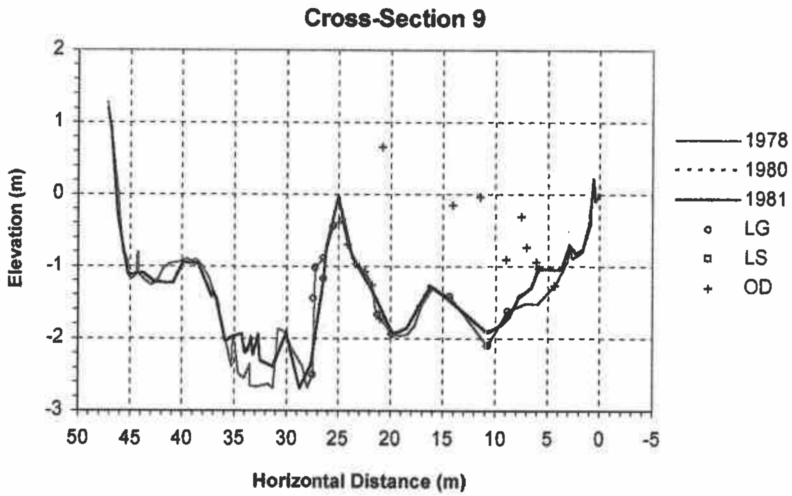

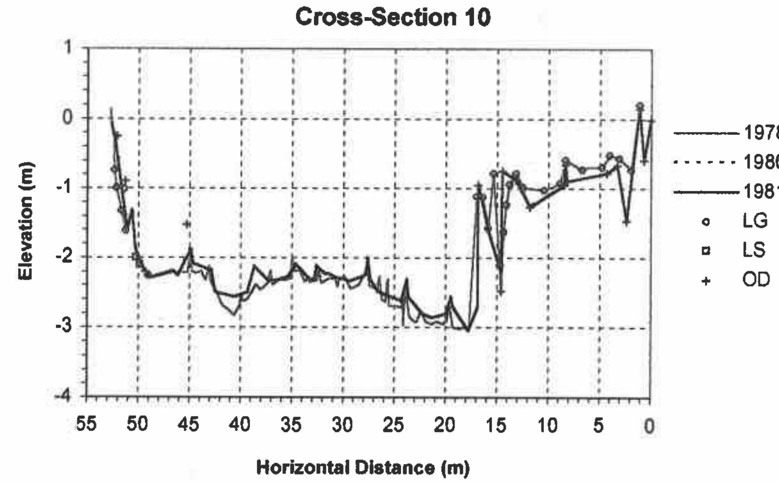

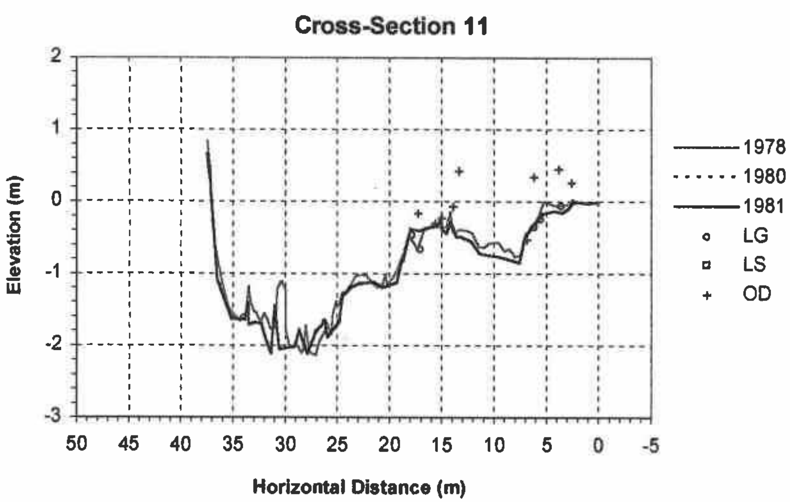

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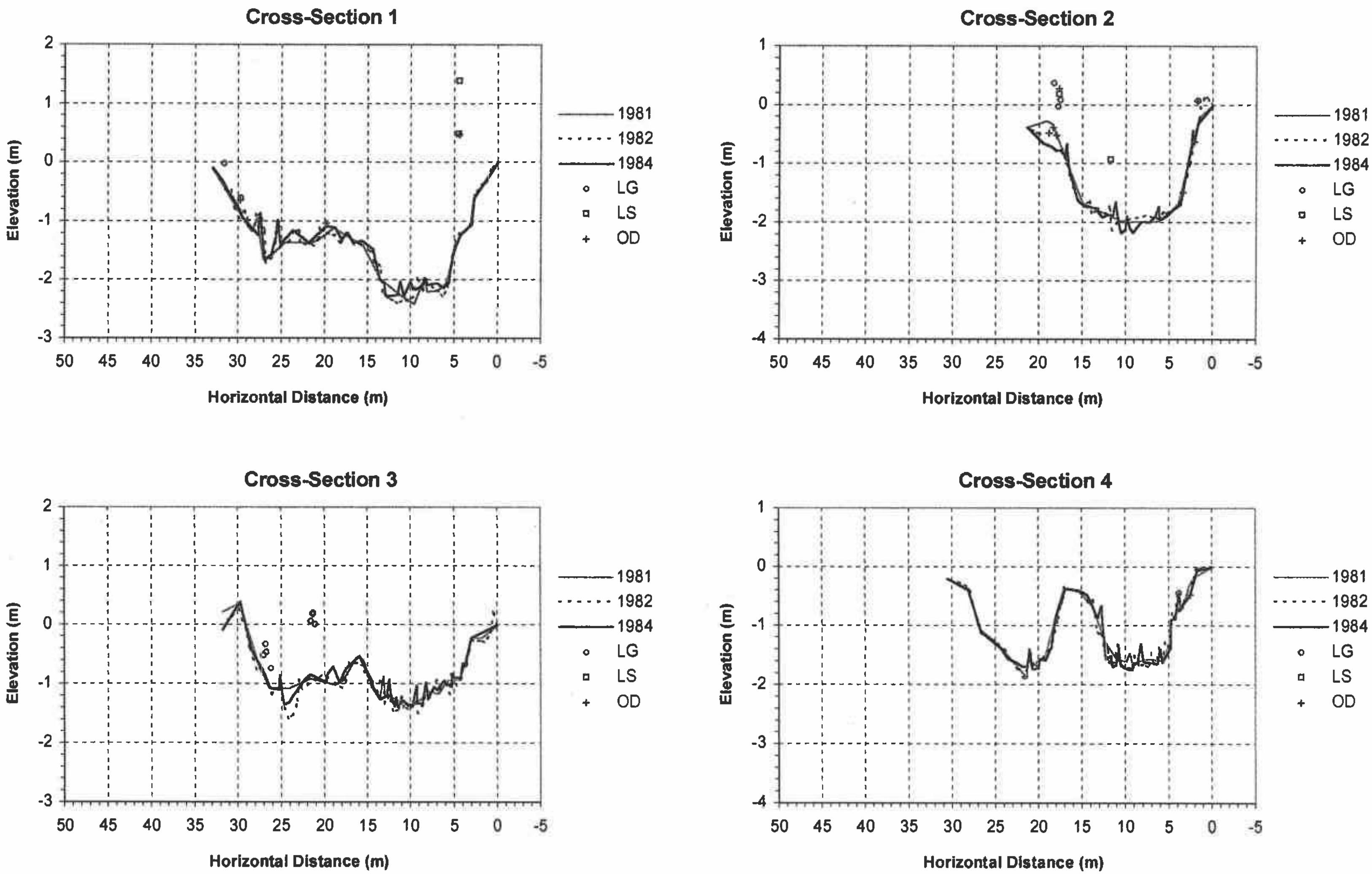


Figure B.7. Filtered cross section profile plots for middle Lookout Creek (LOM) site, 1981-84.

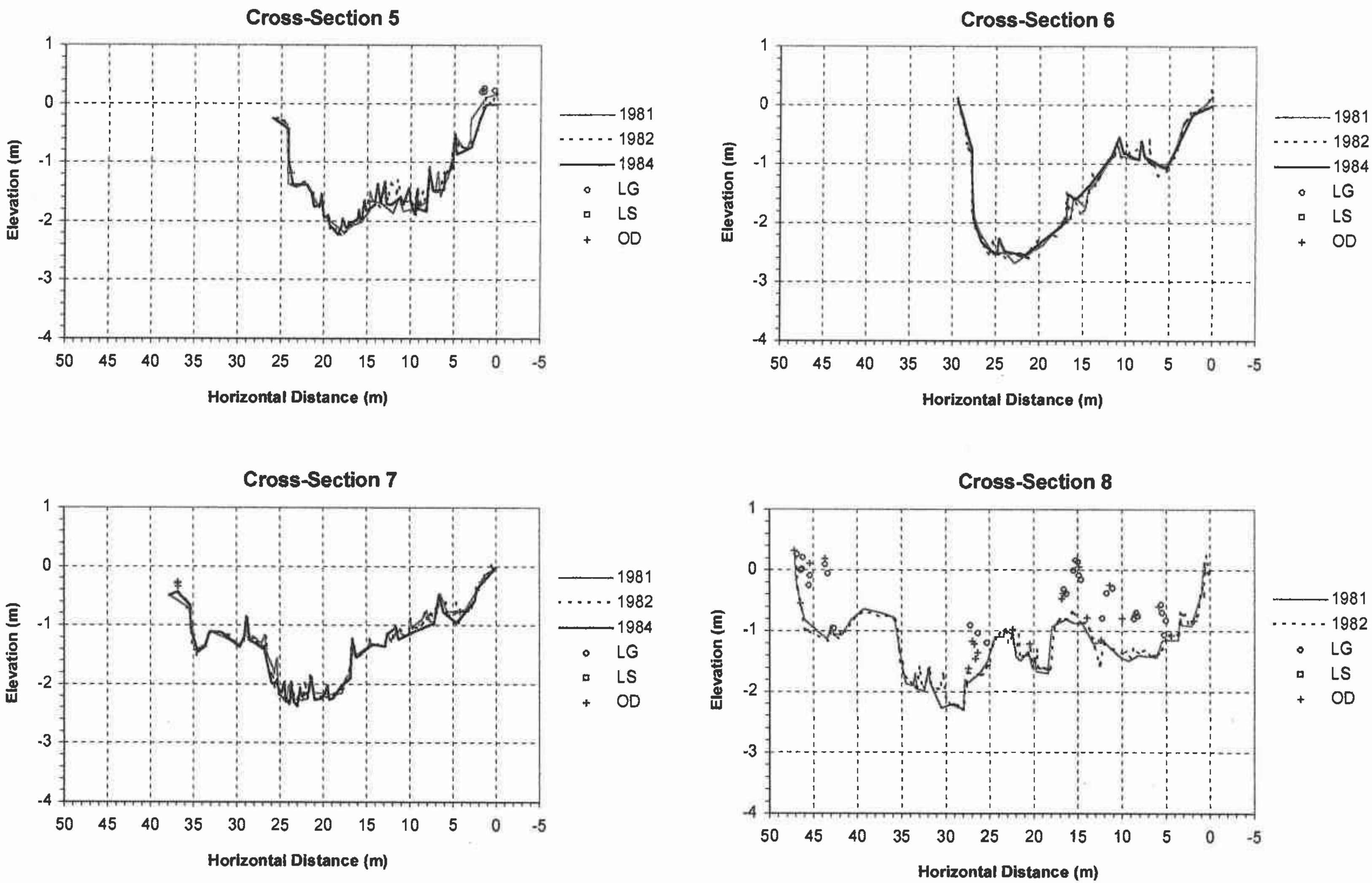
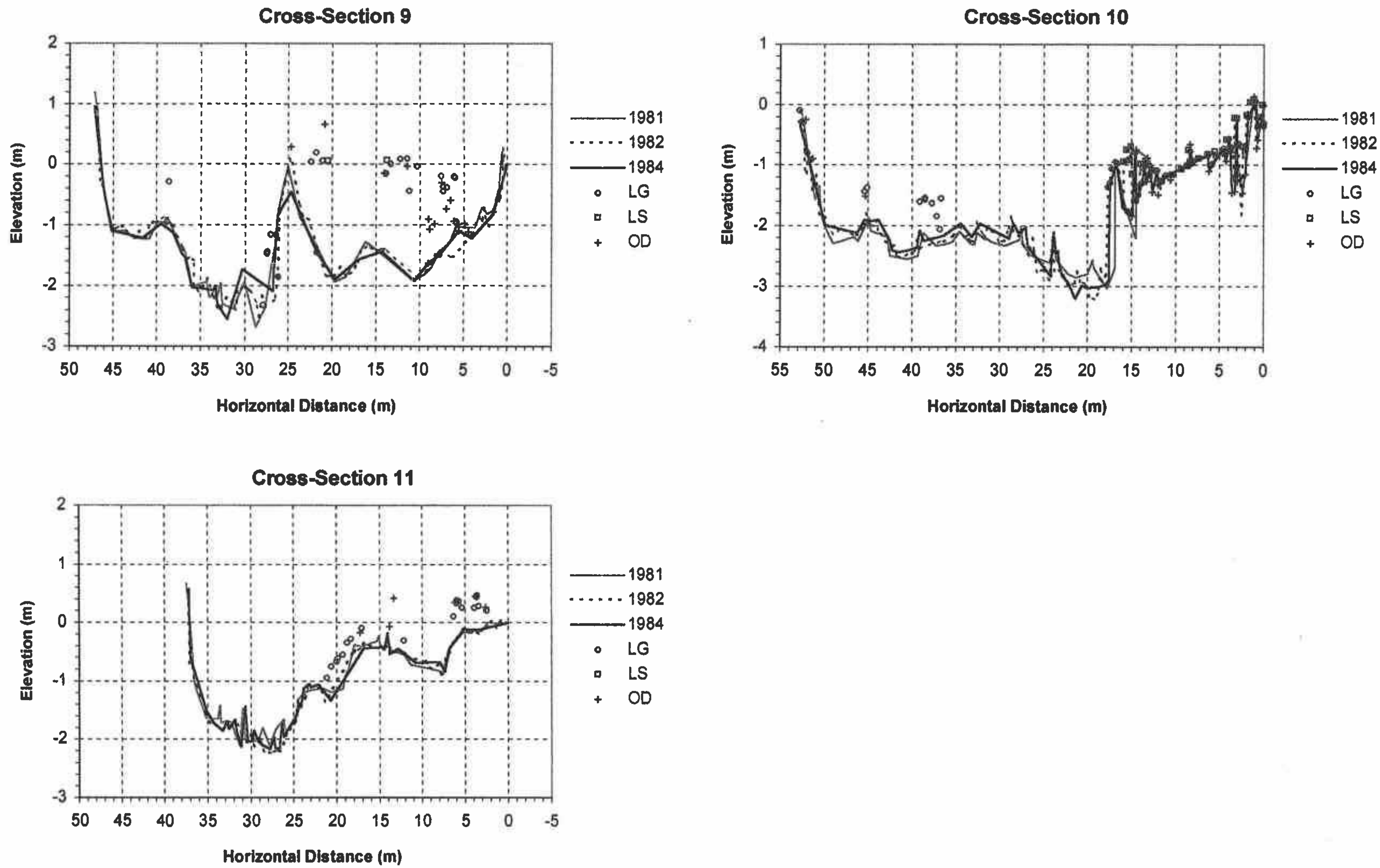


Figure B.7. (continued)



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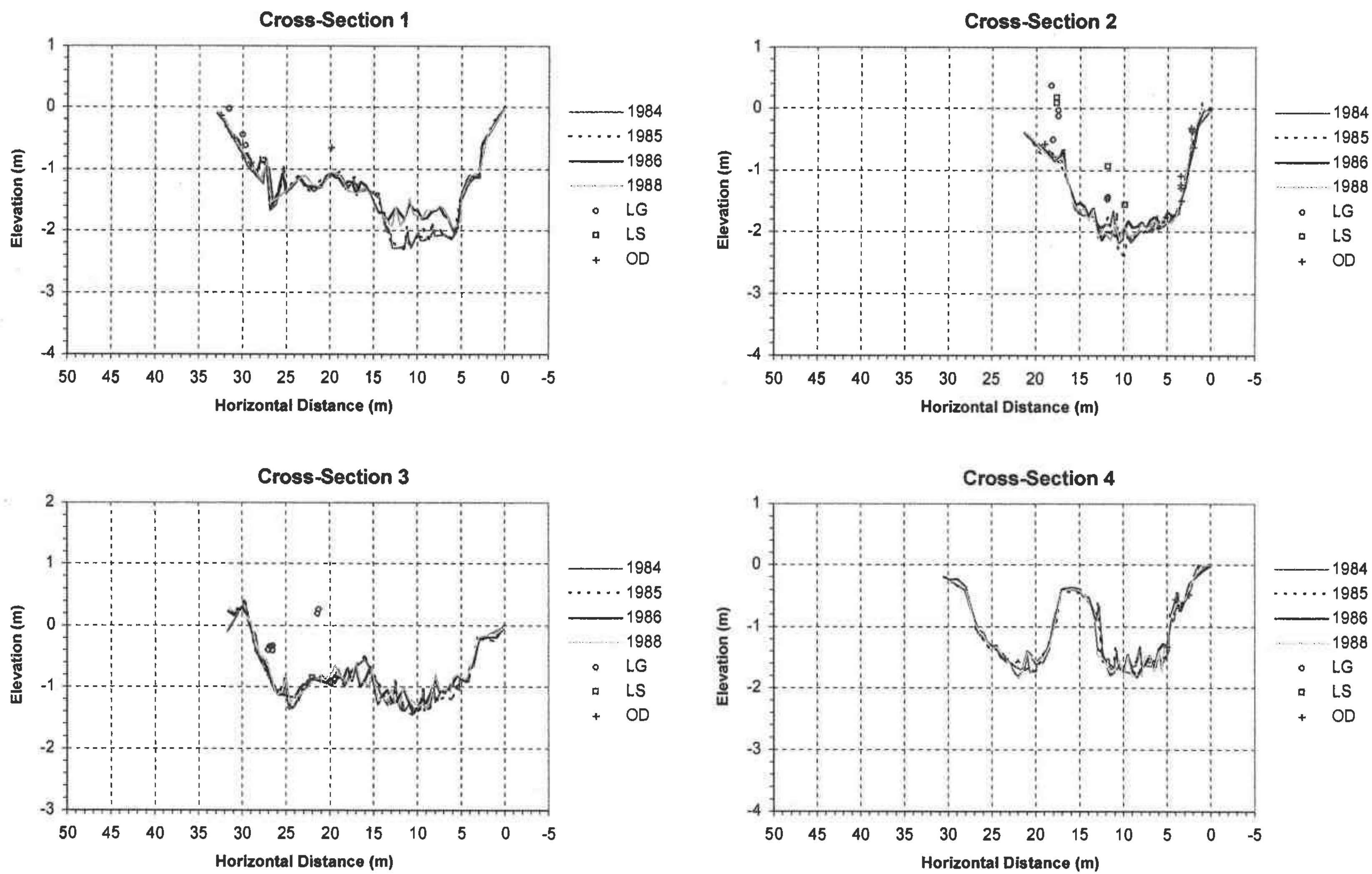


Figure B.8. Filtered cross section profile plots for middle Lookout Creek (LOM) site, 1984-88.

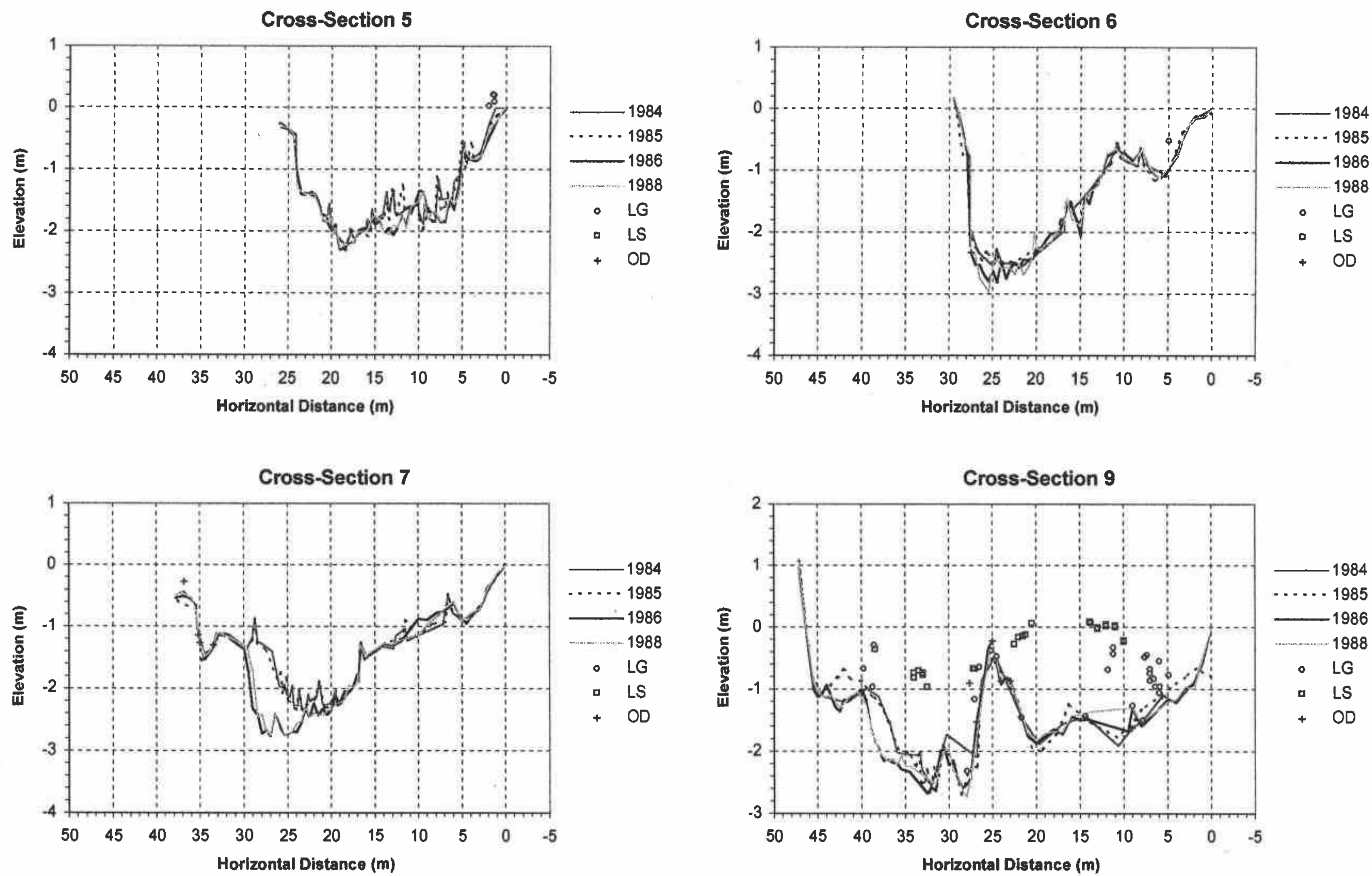
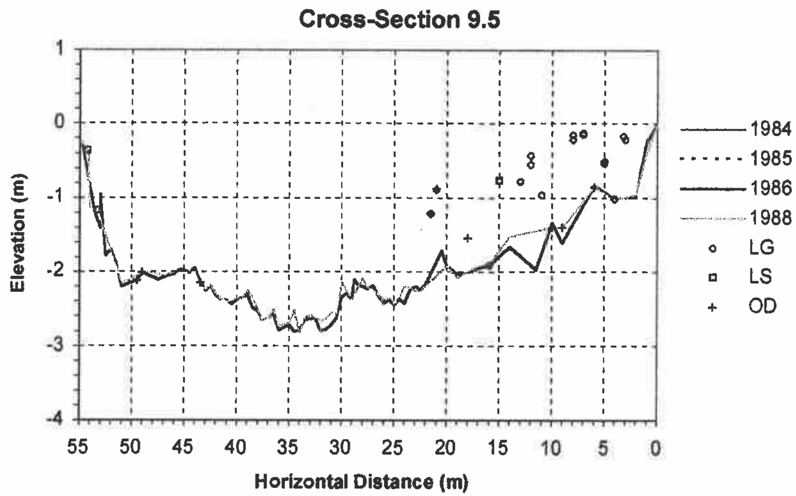
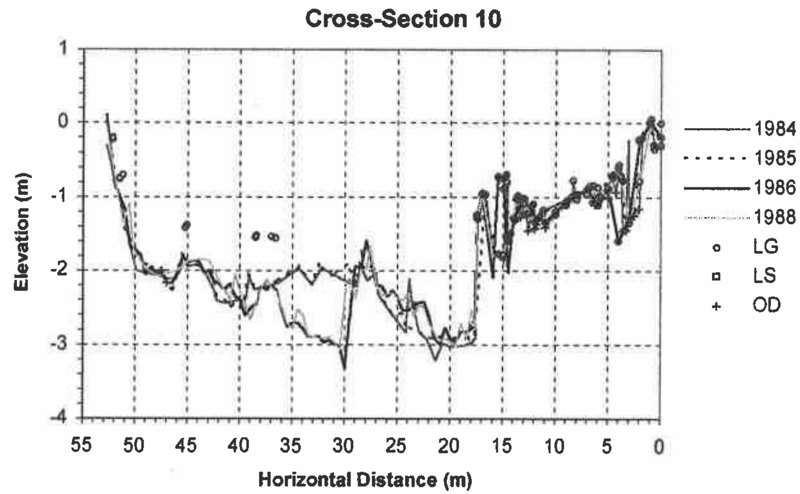


Figure B.8. (continued)





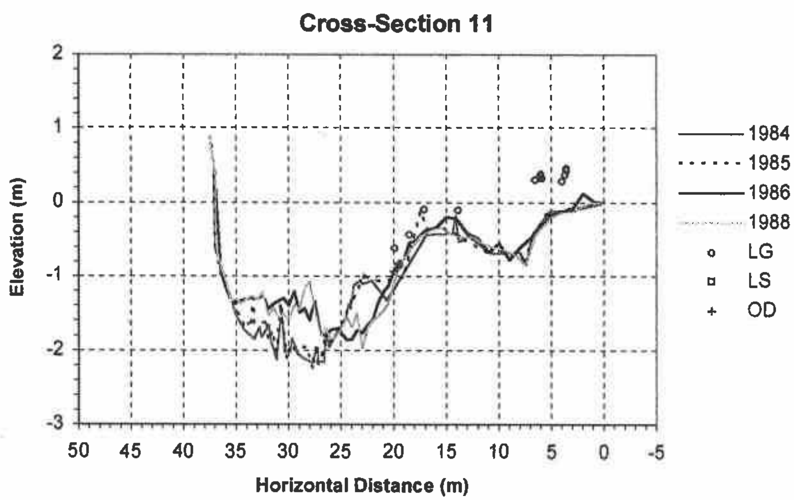


Figure B.8. (continued)

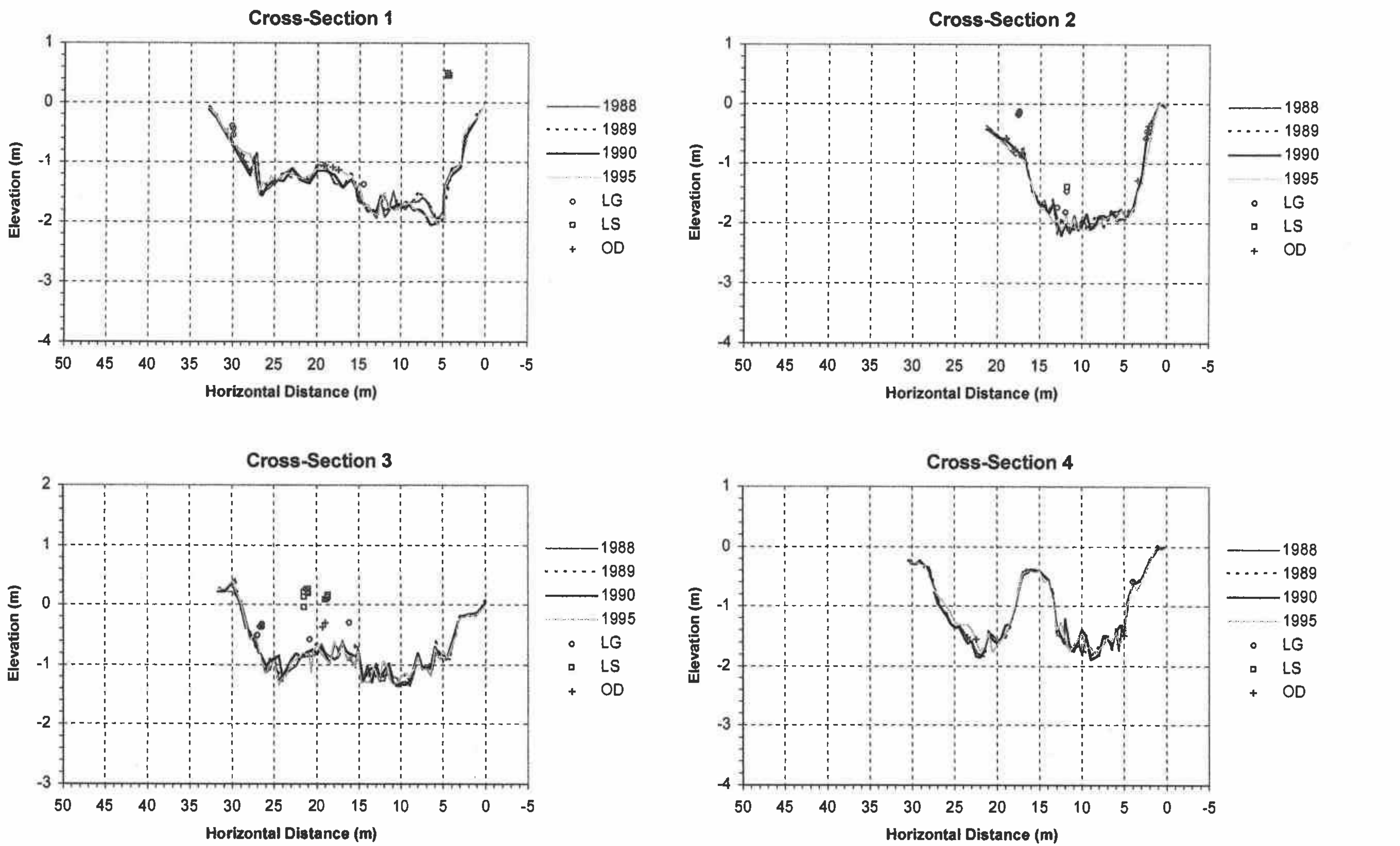


Figure B.9. Filtered cross section profile plots for middle Lookout Creek (LOM) site, 1988-95.

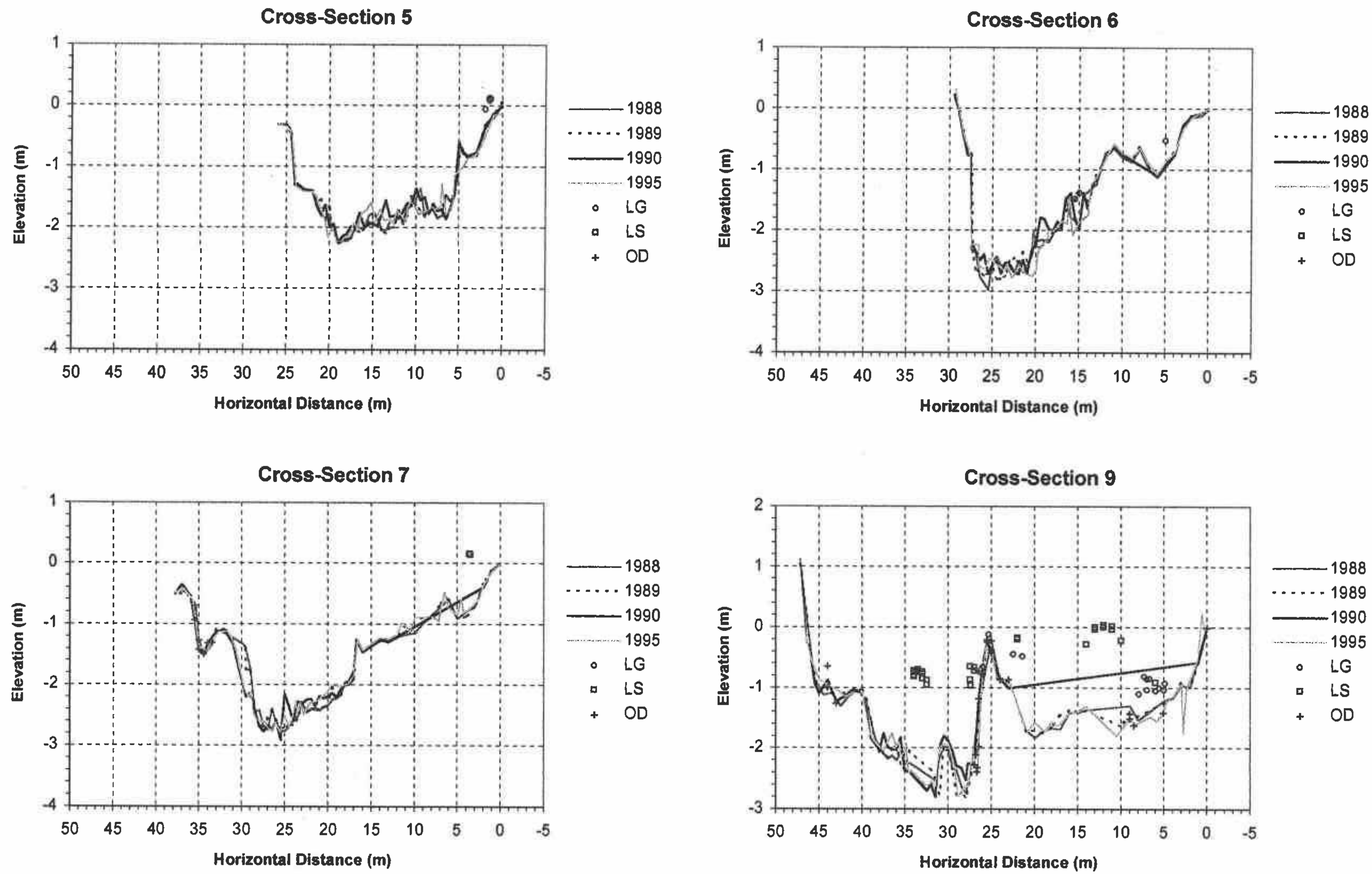


Figure B.9. (continued)

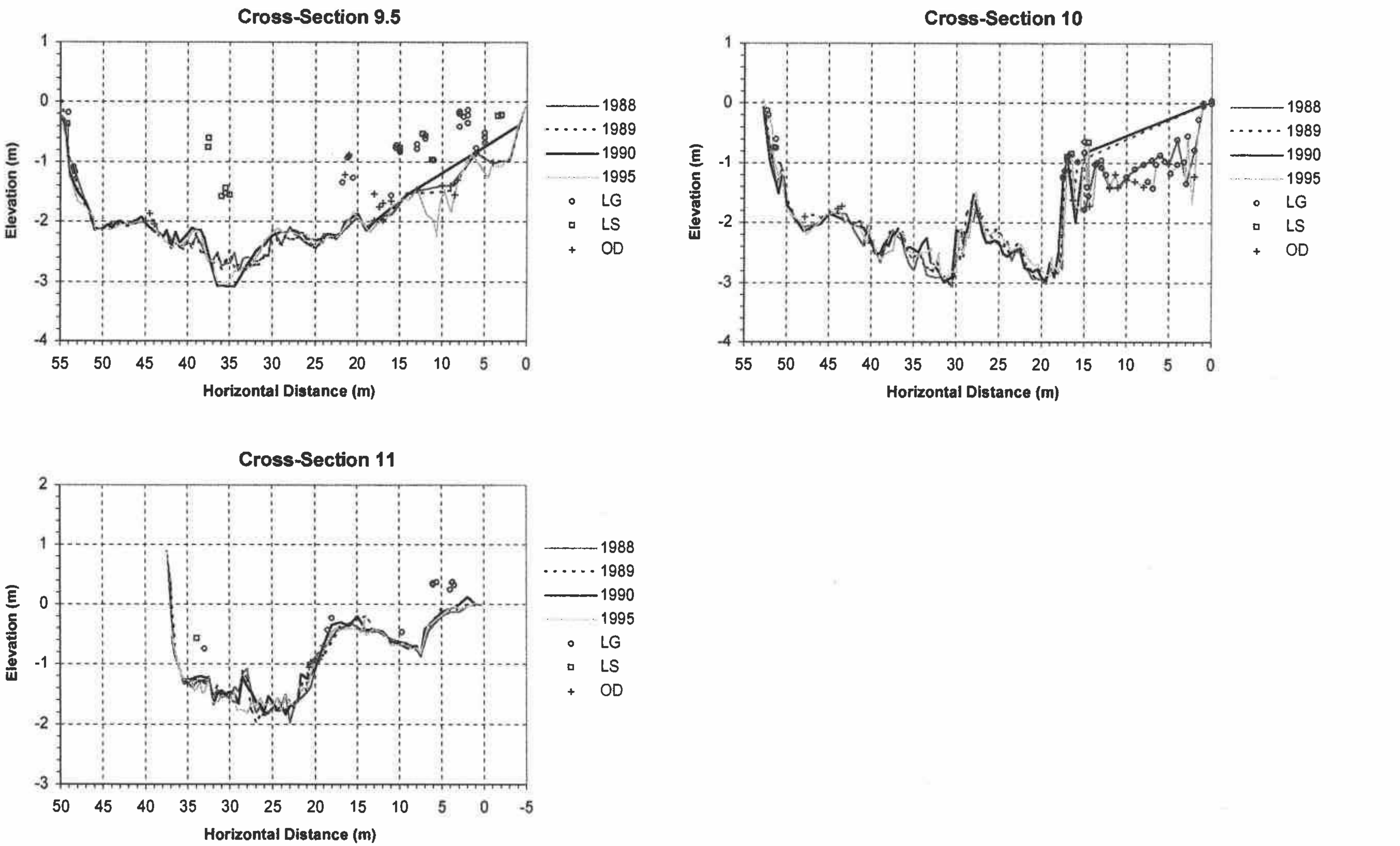


Figure B.9. (continued)

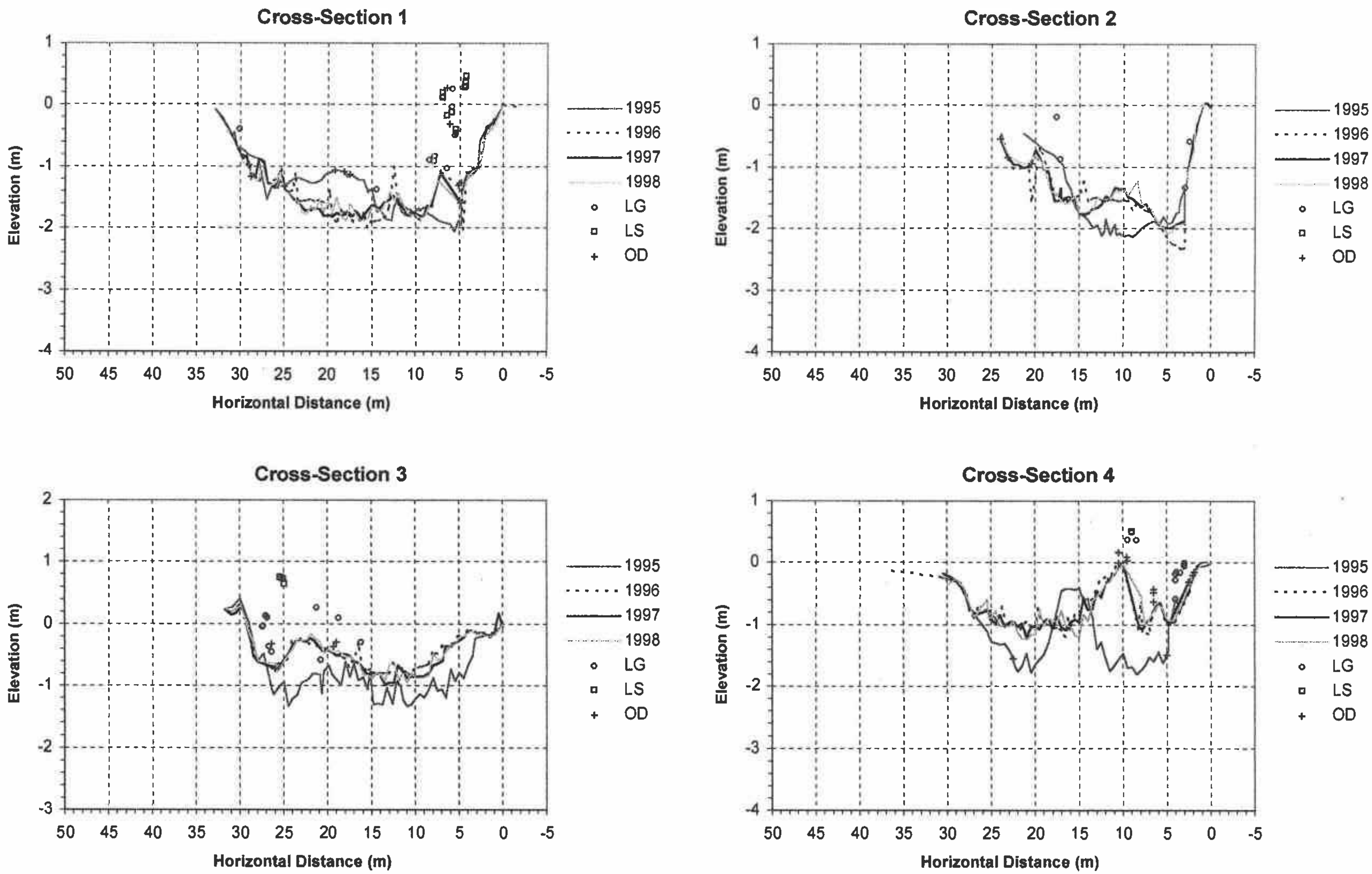


Figure B.10. Filtered cross section profile plots for middle Lookout Creek (LOM) site, 1995-98.

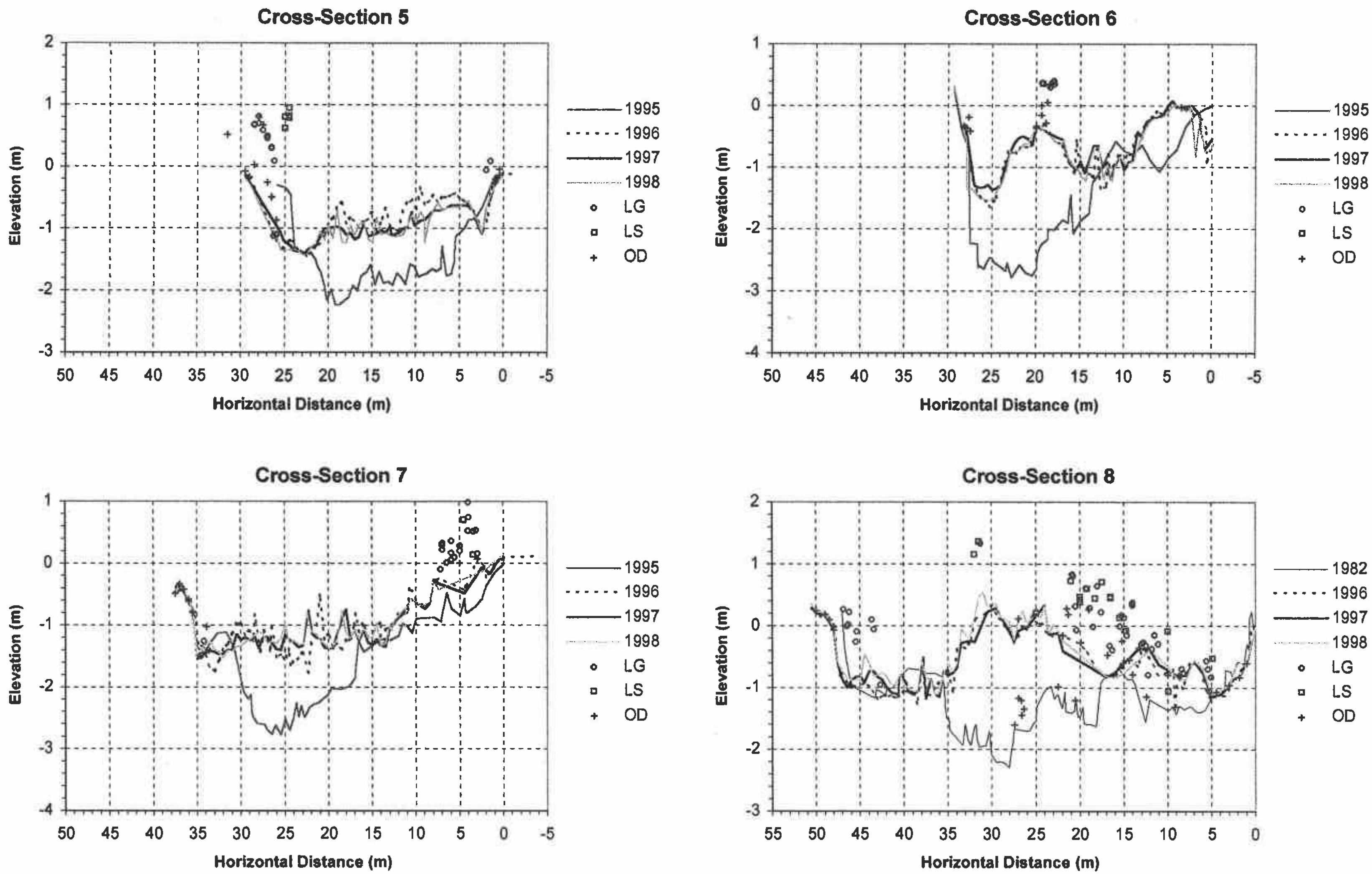


Figure B.10. (continued)

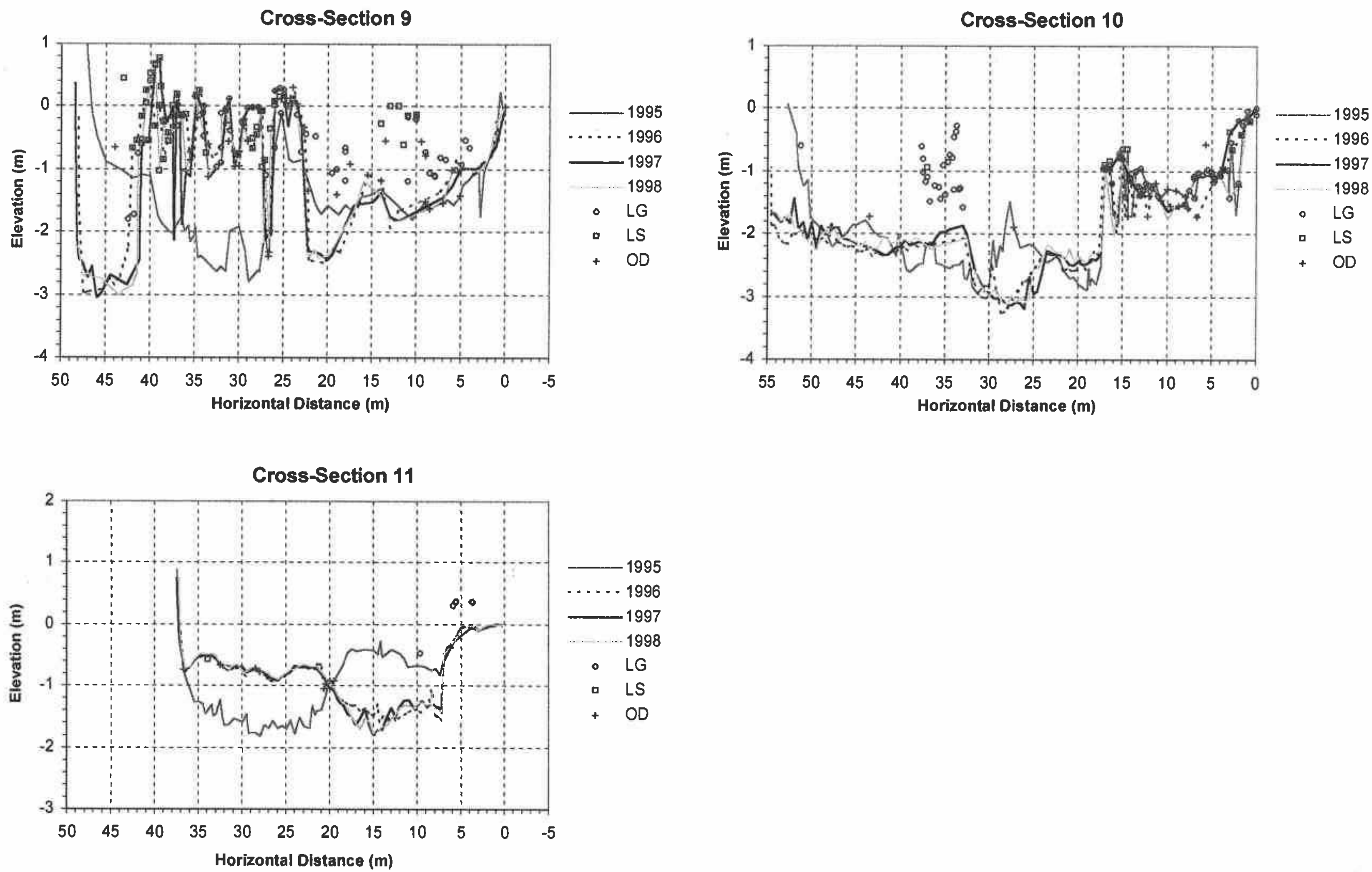


Figure B.10. (continued)

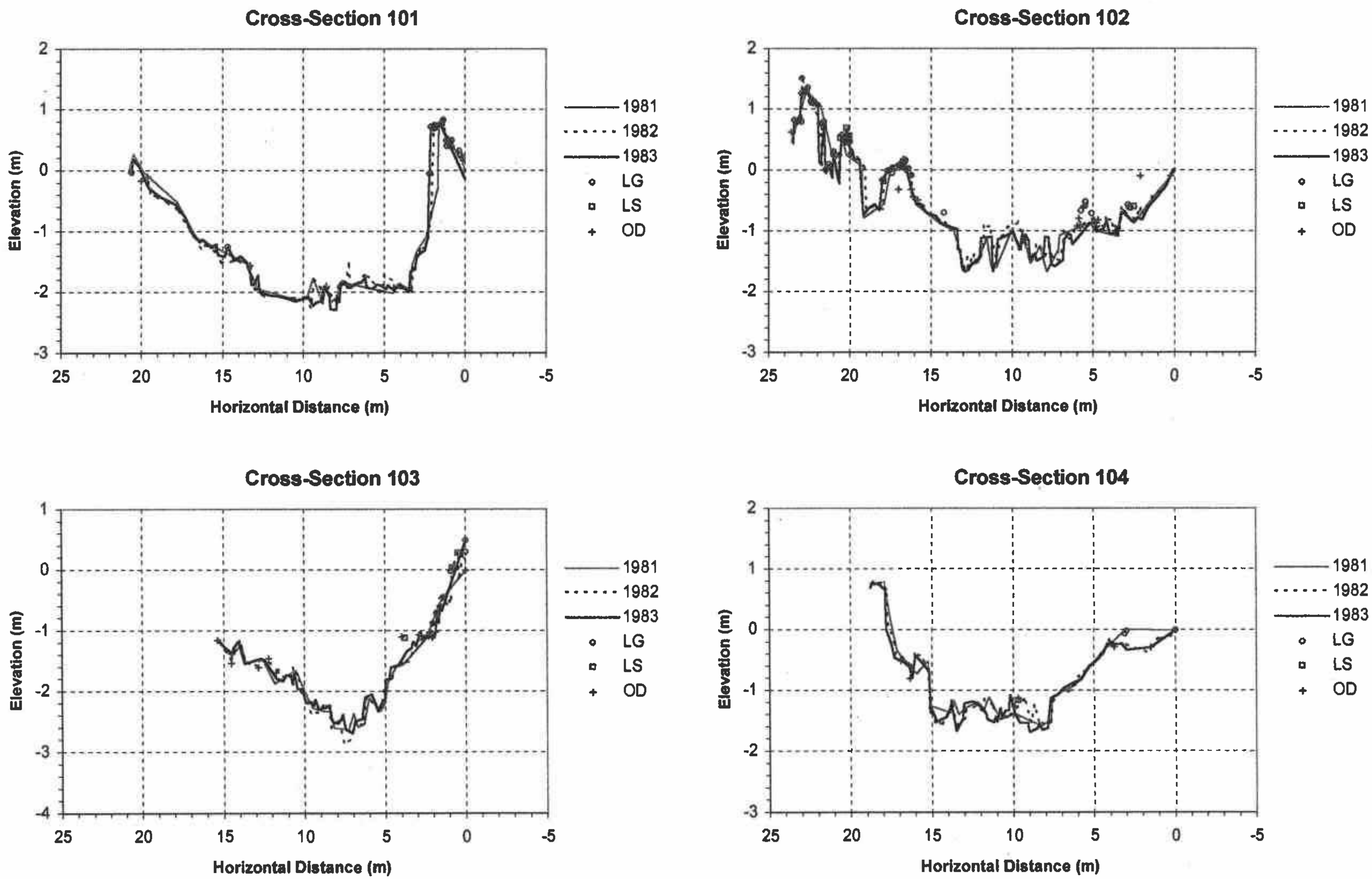


Figure B.11. Filtered cross section profile plots for Mack Creek Clearcut (MCC) site, 1981-83.

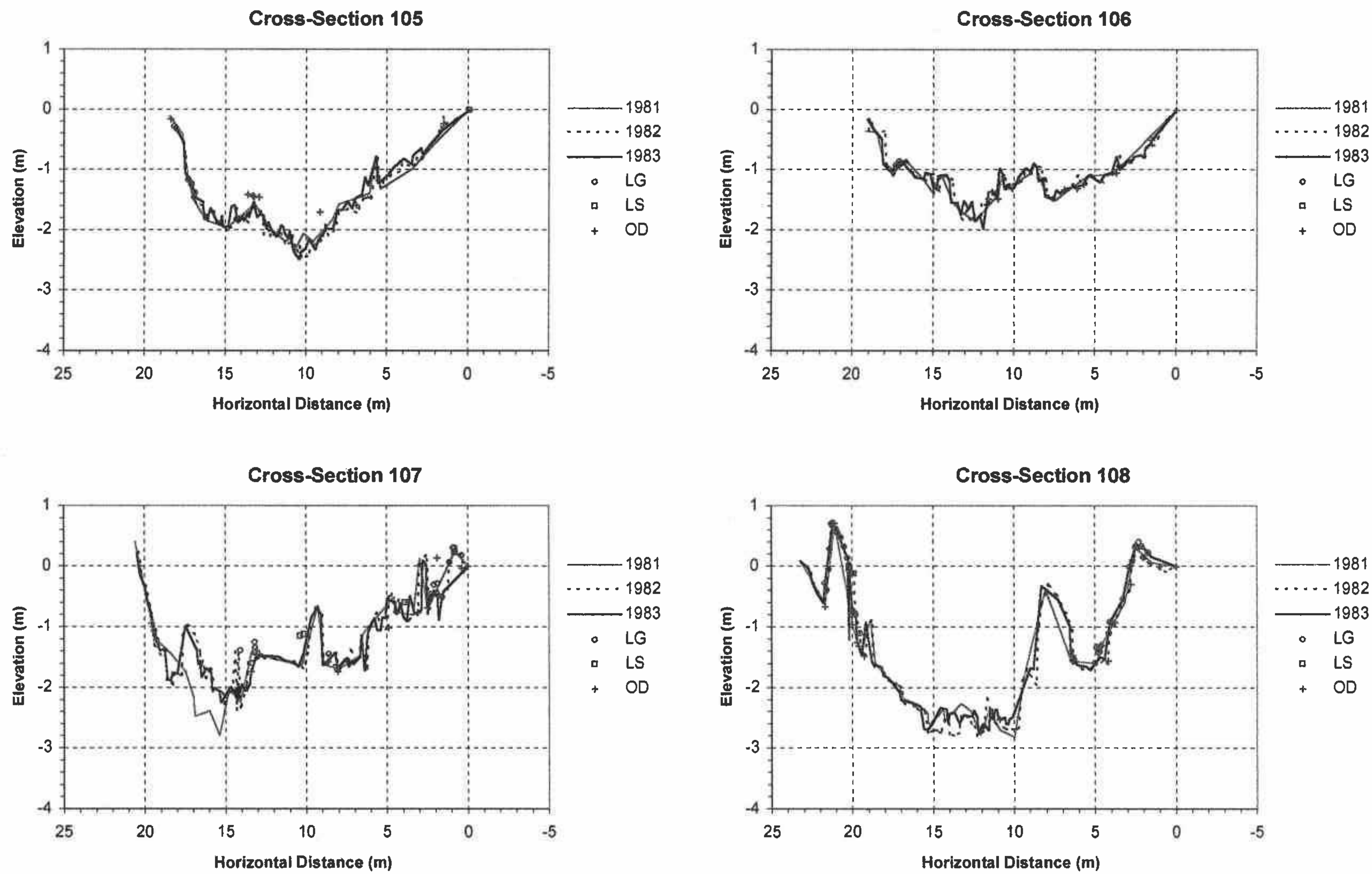


Figure B.11. (continued)

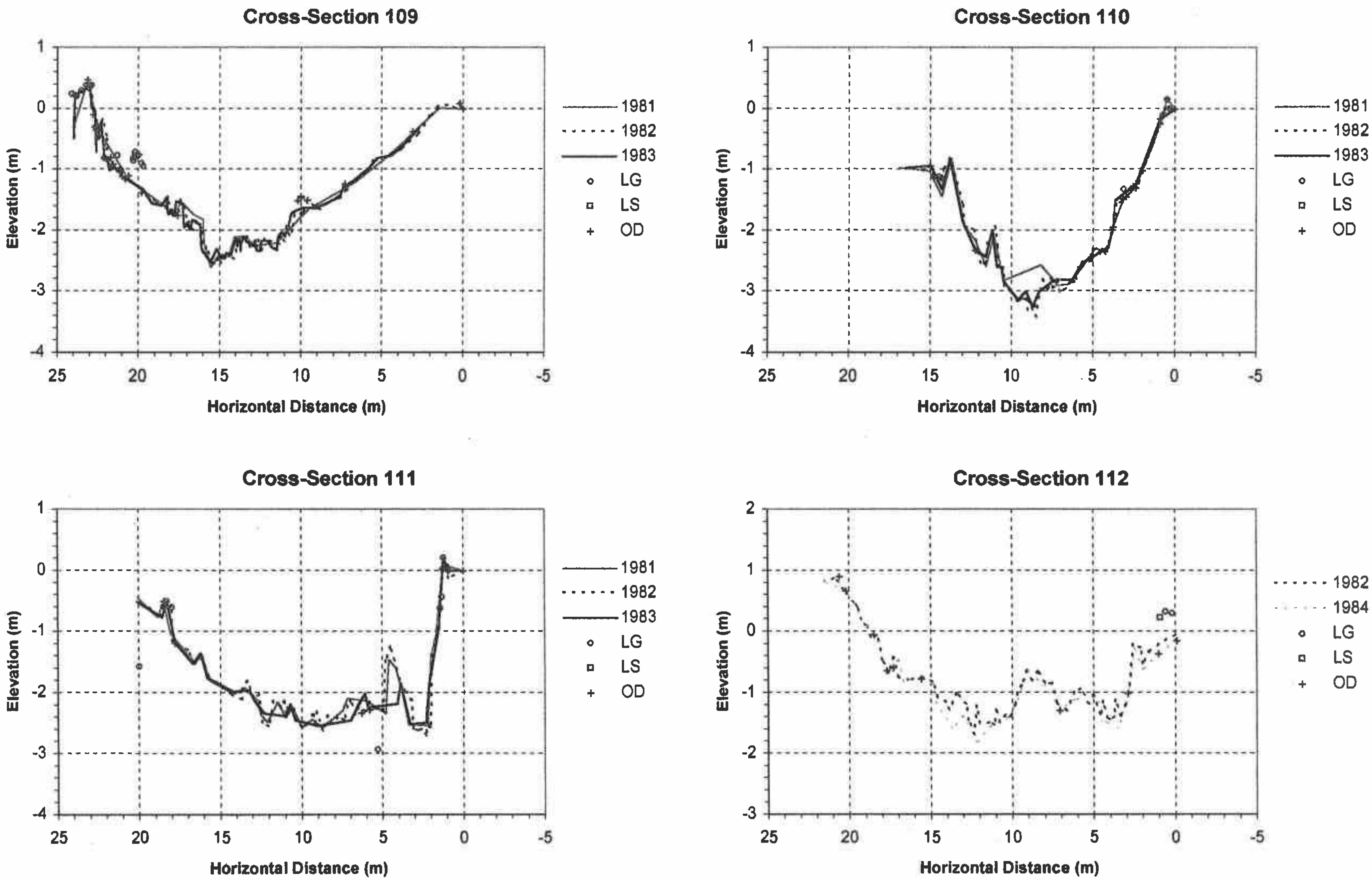


Figure B.11. (continued)

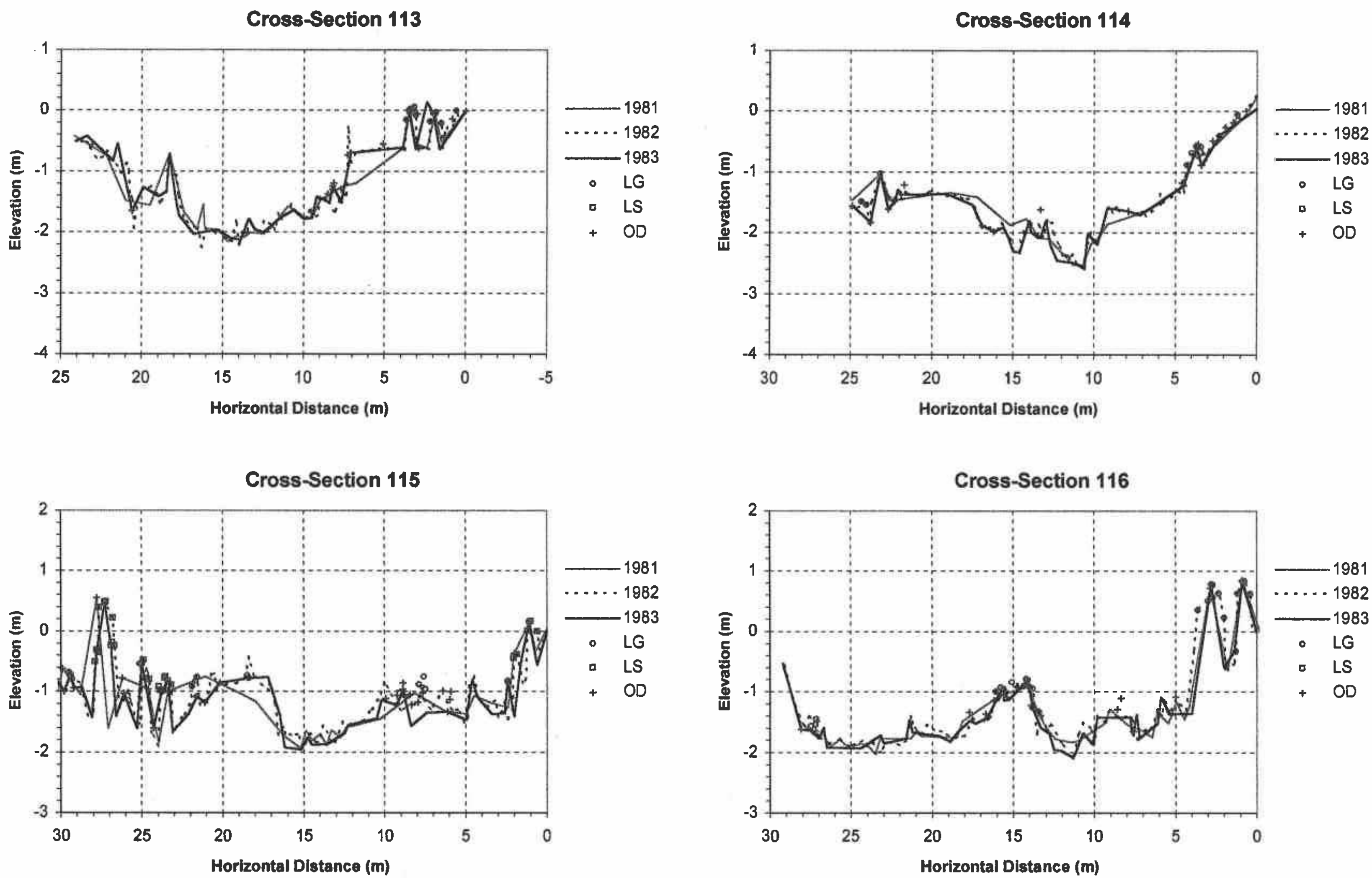


Figure B.11. (continued)

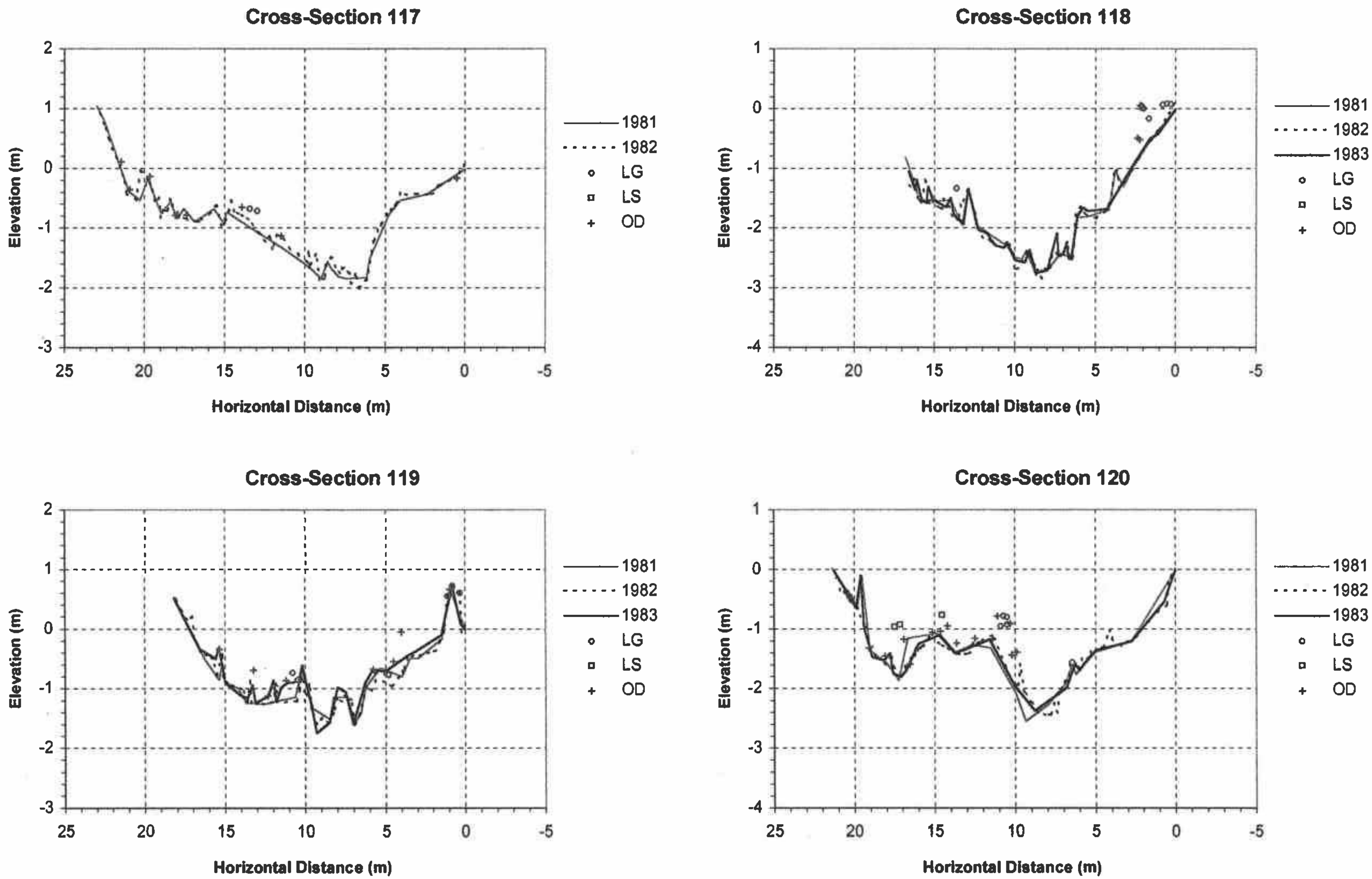


Figure B.11. (continued)

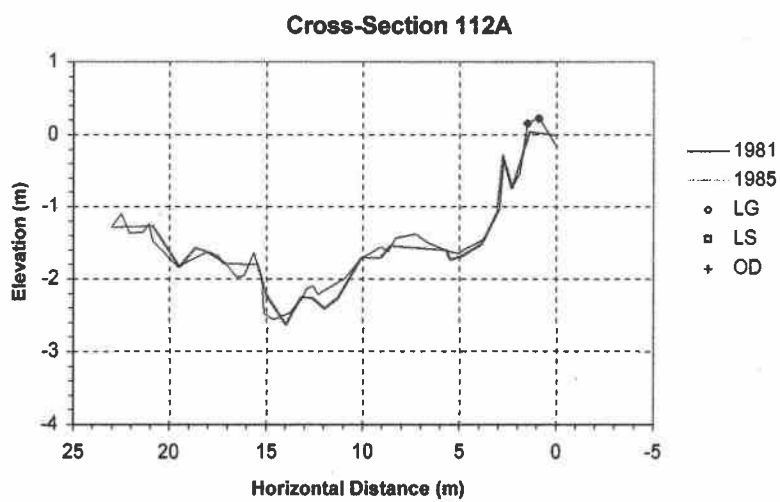


Figure B.11. (continued)

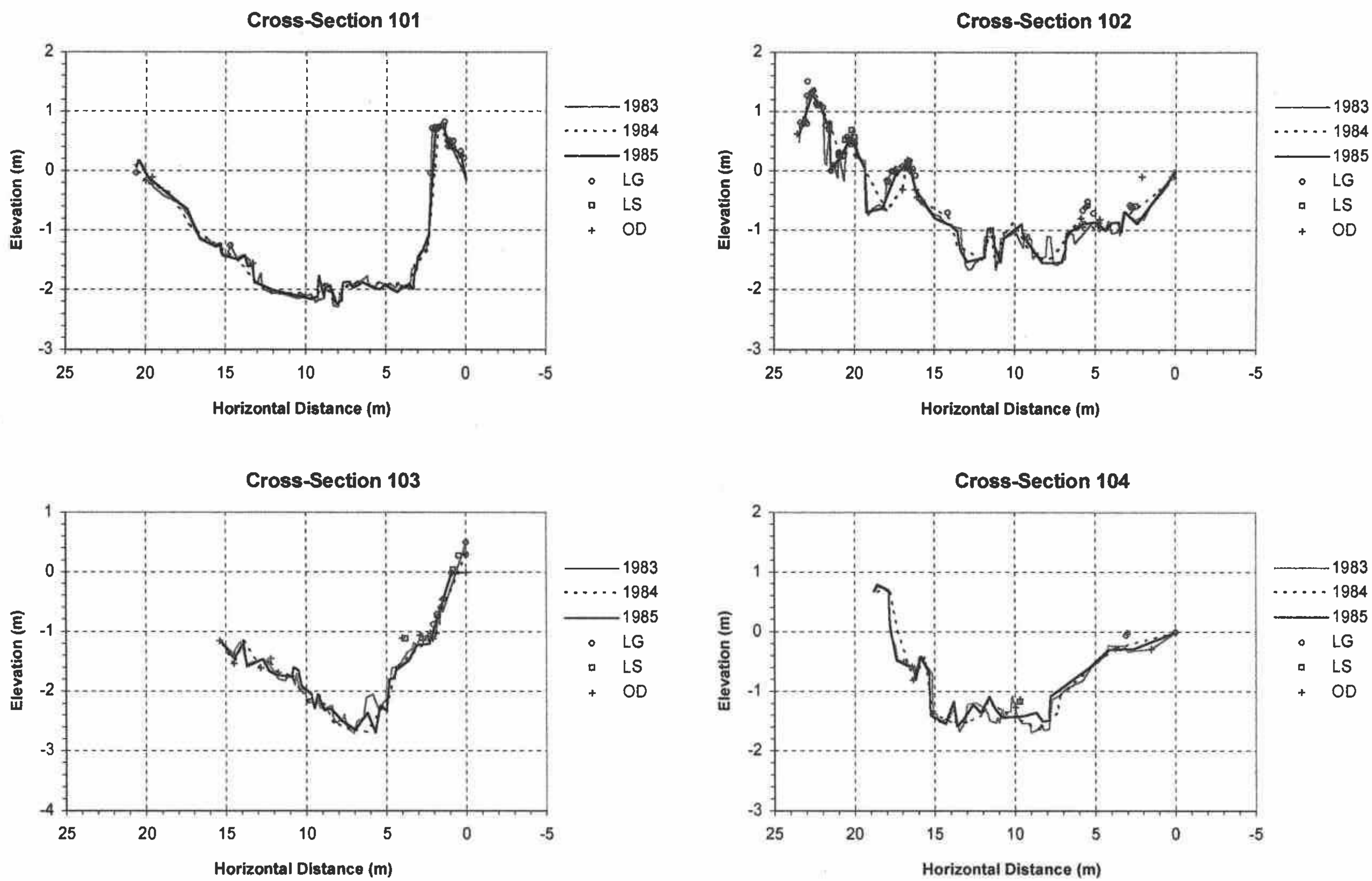


Figure B.12. Filtered cross section profile plots for Mack Creek Clearcut (MCC) site, 1983-85.

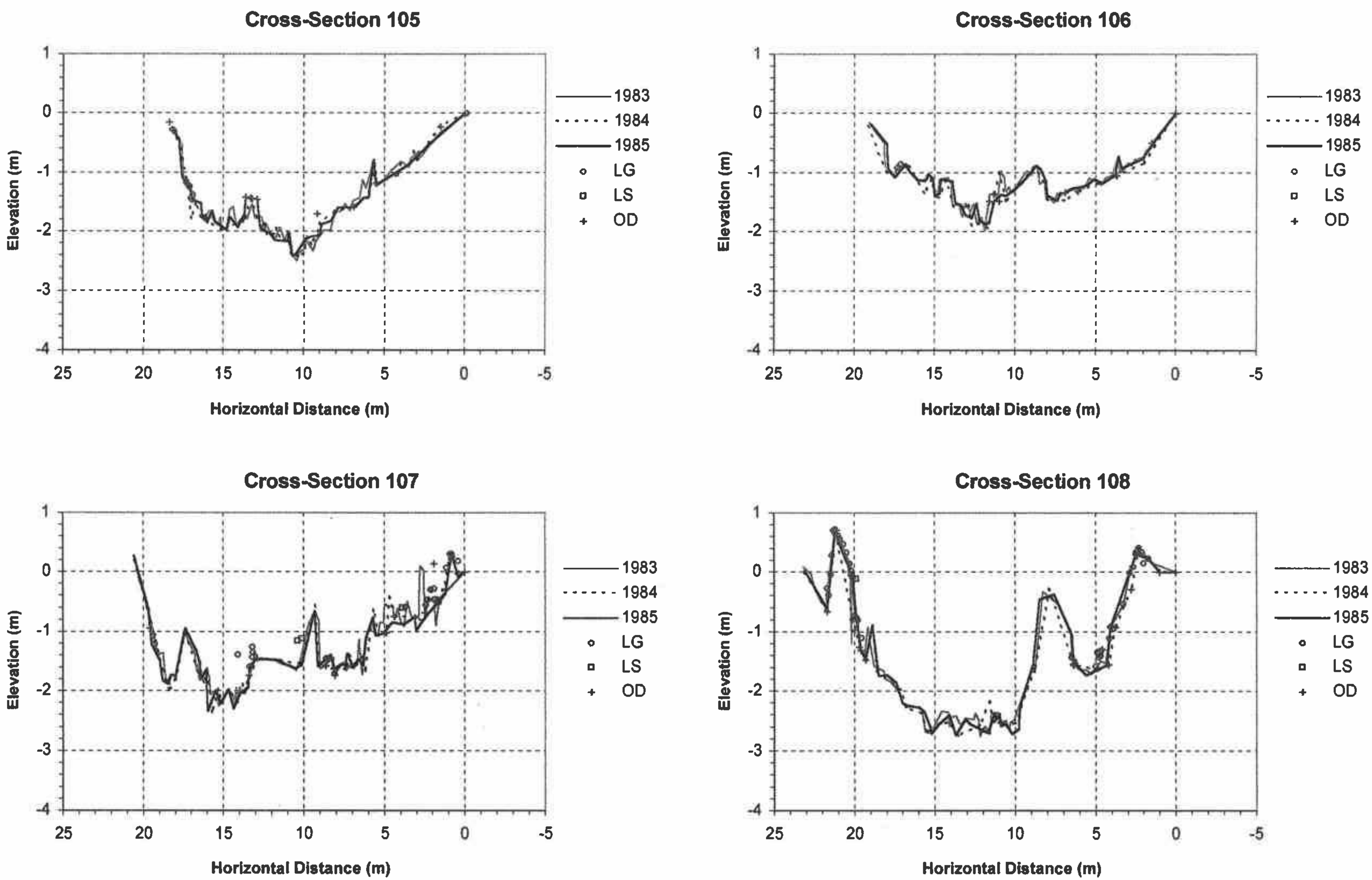
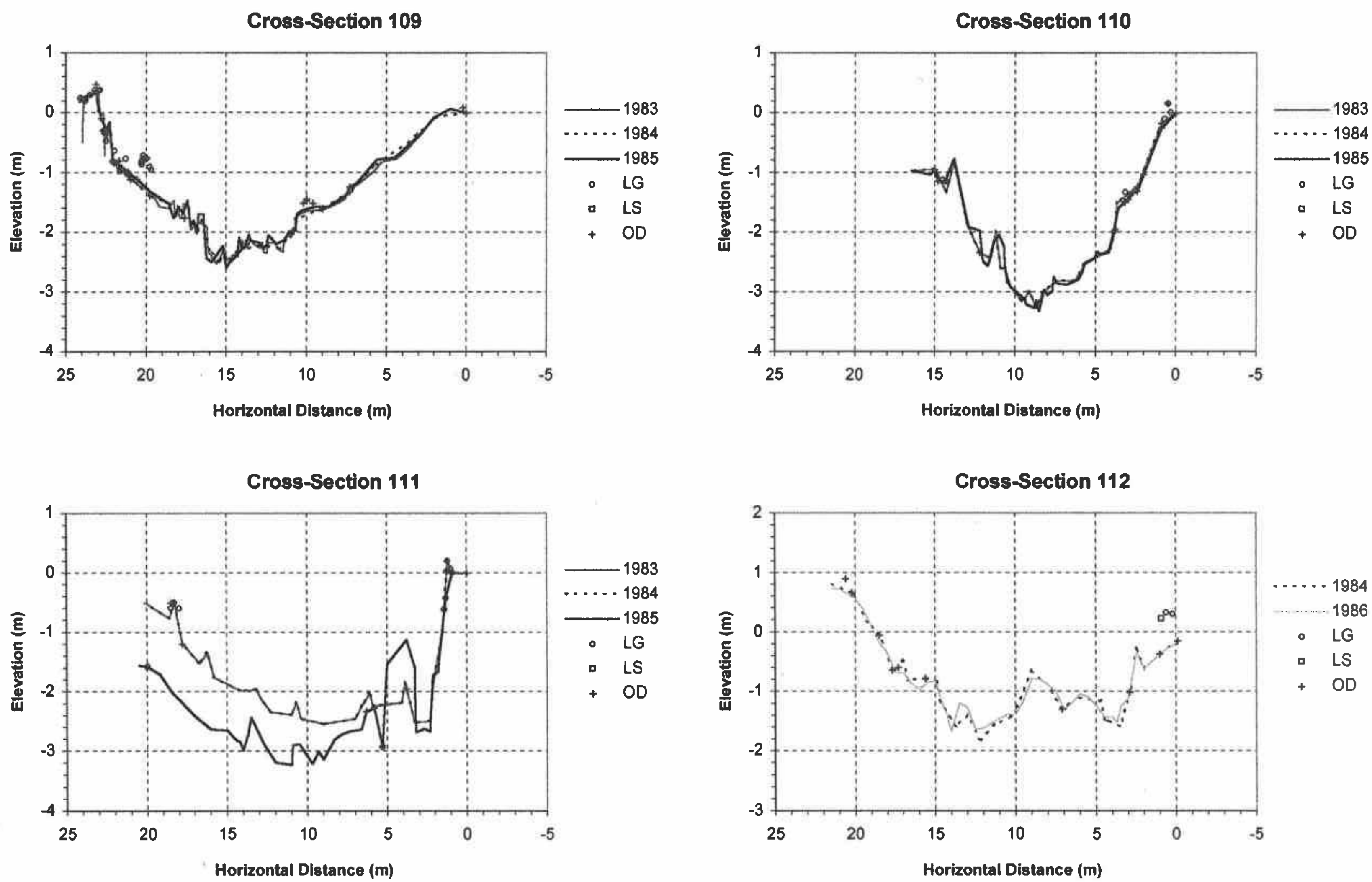


Figure B.12. (continued)



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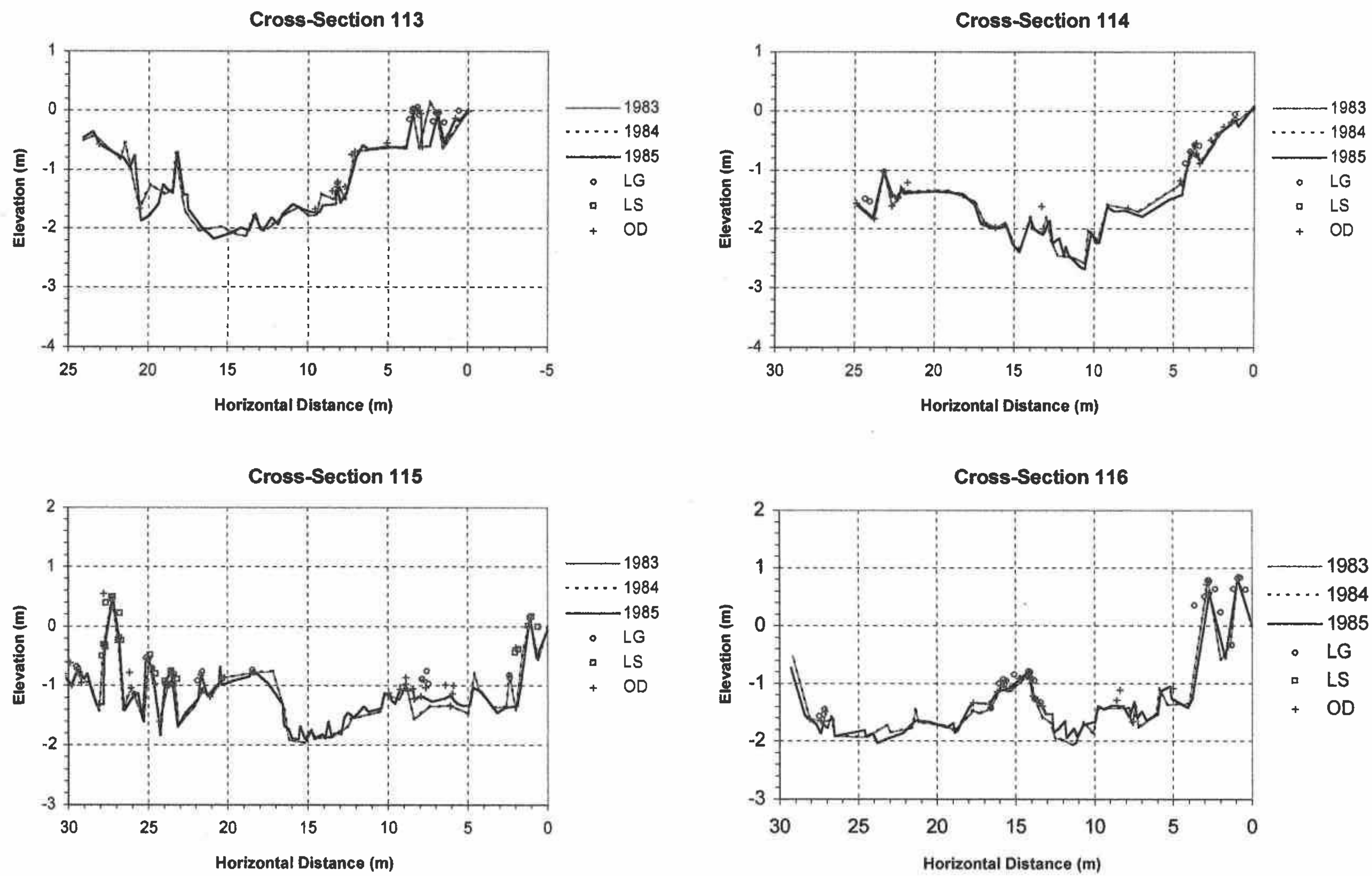


Figure B.12. (continued)

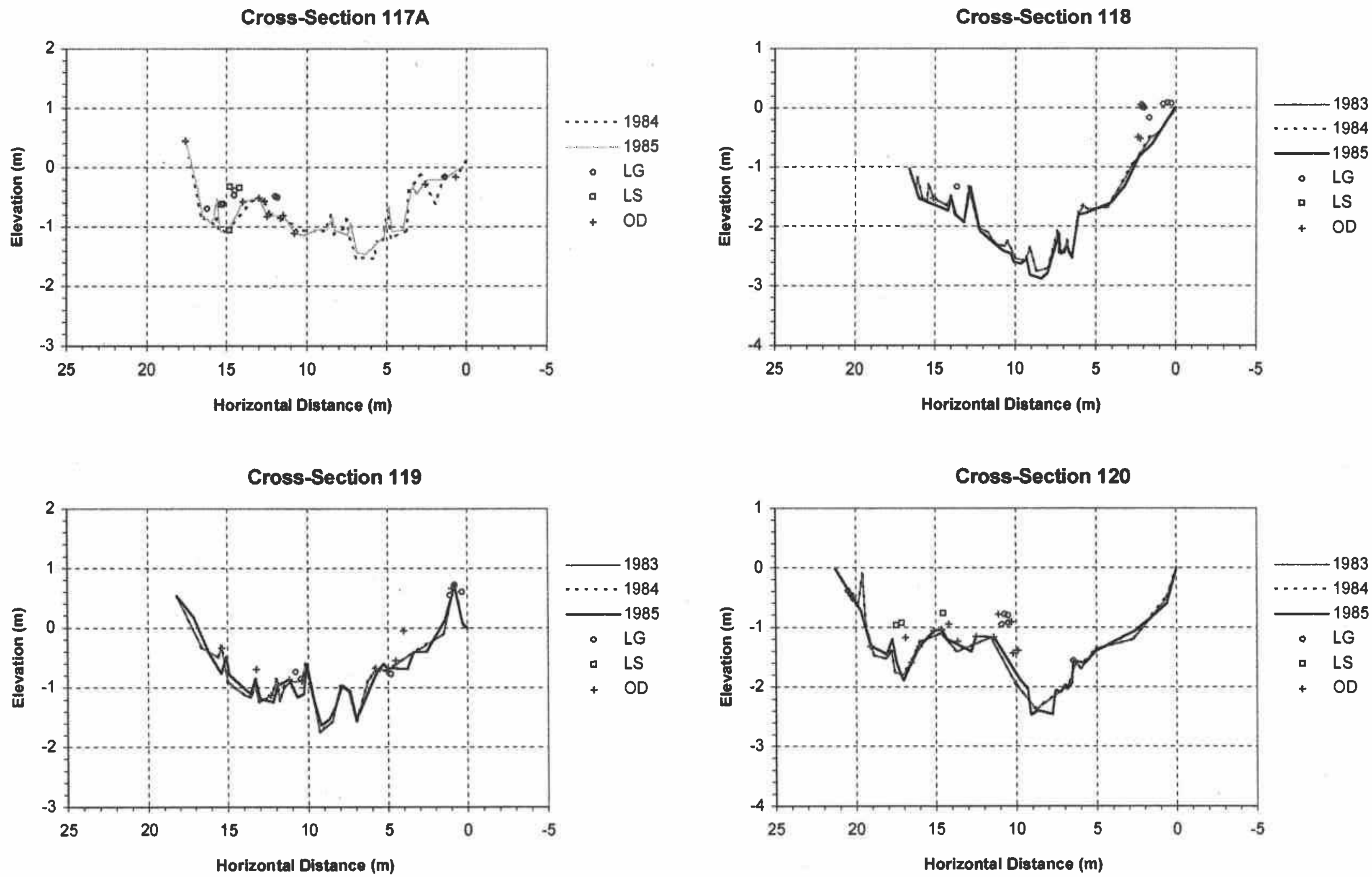


Figure B.12. (continued)

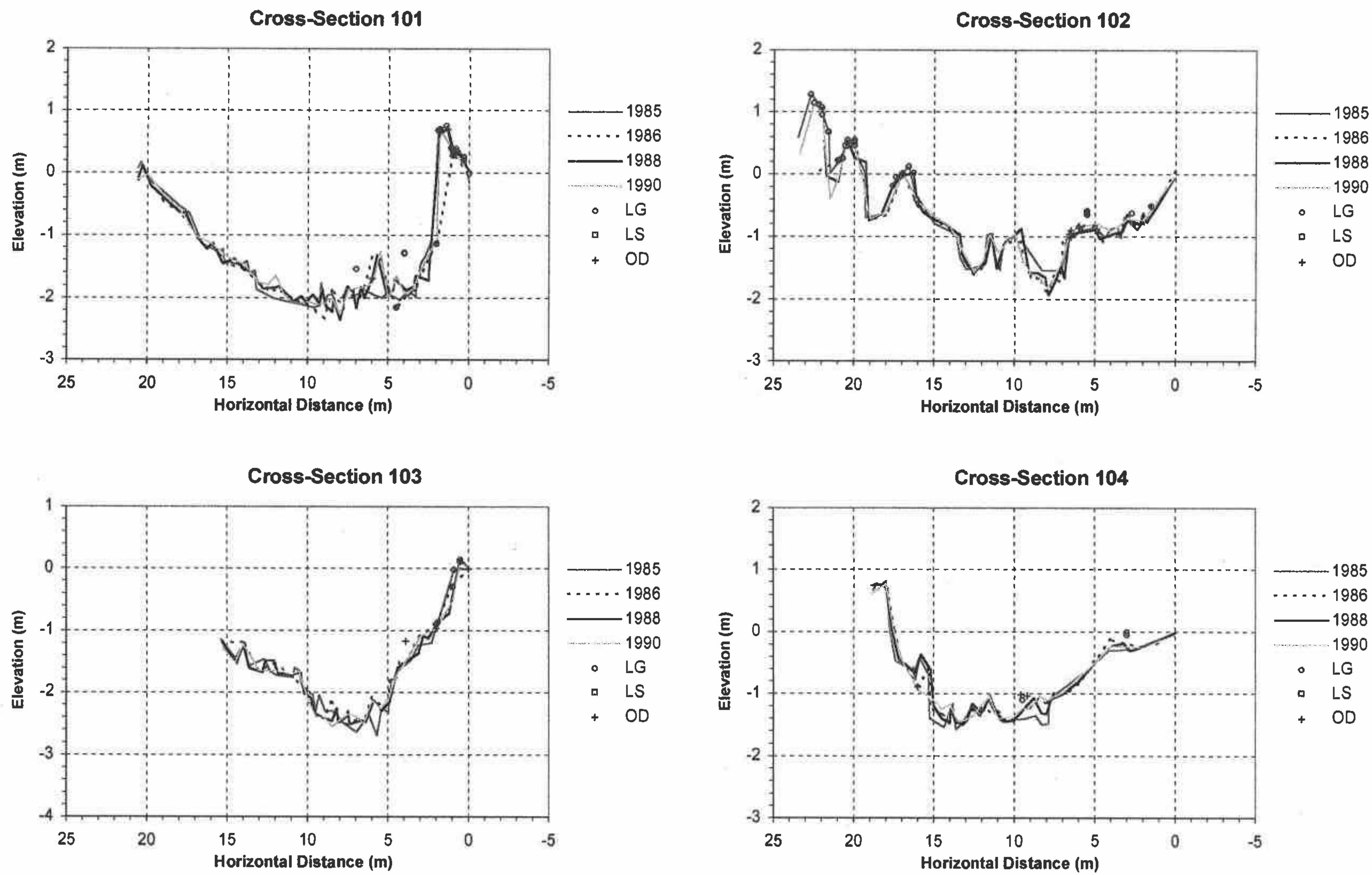
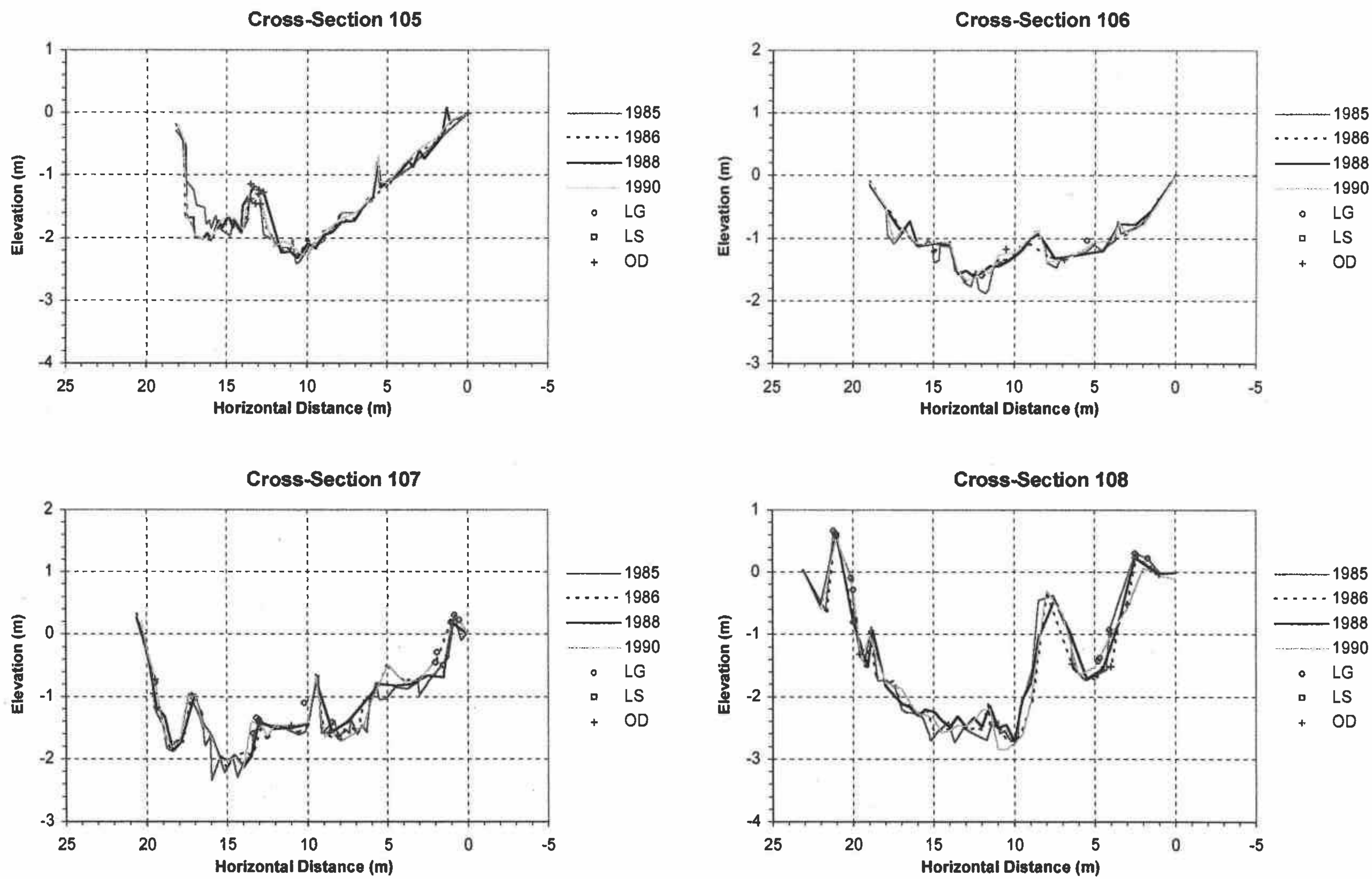


Figure B.13. Filtered cross section profile plots for Mack Creek Clearcut (MCC) site, 1985-90.



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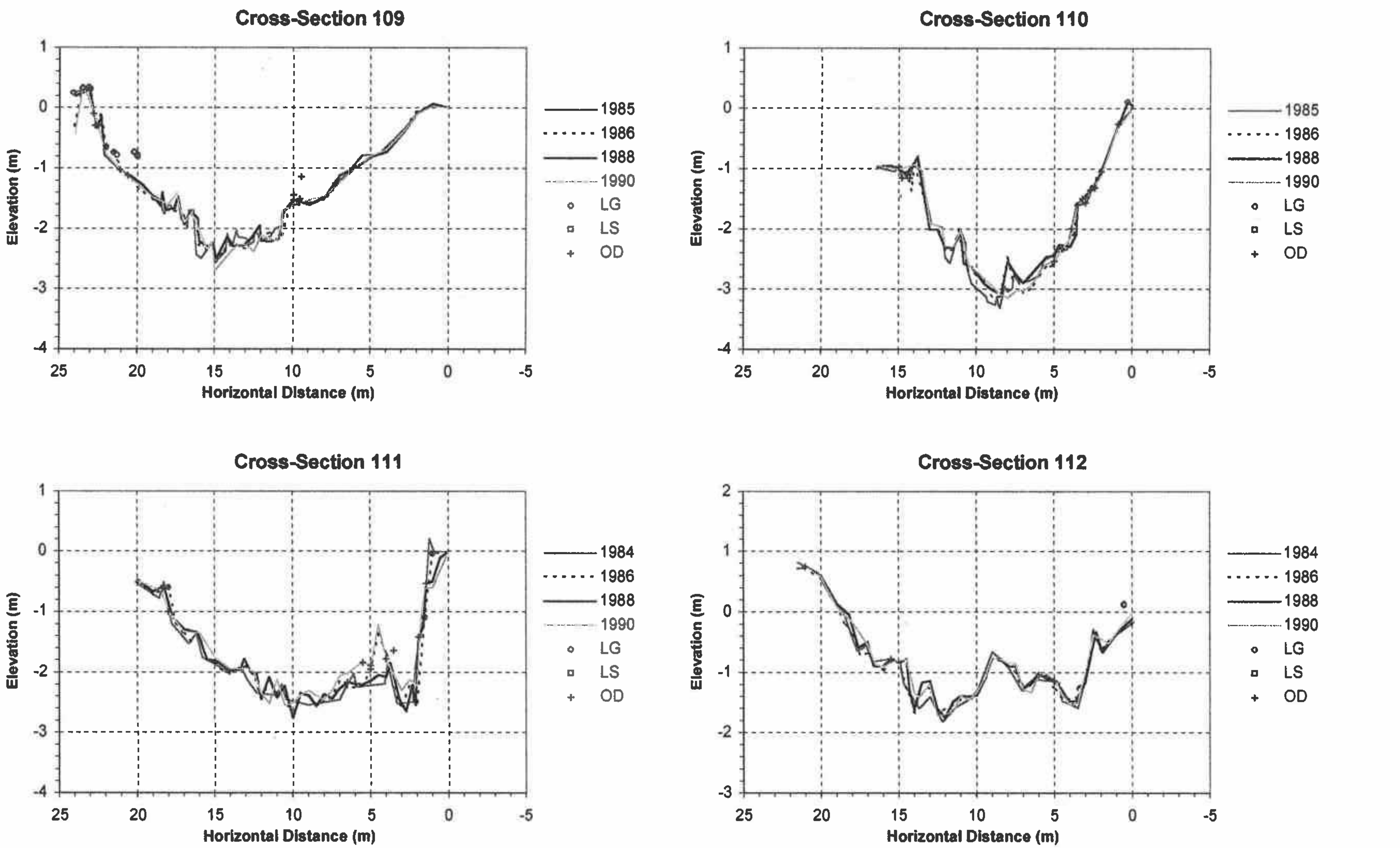

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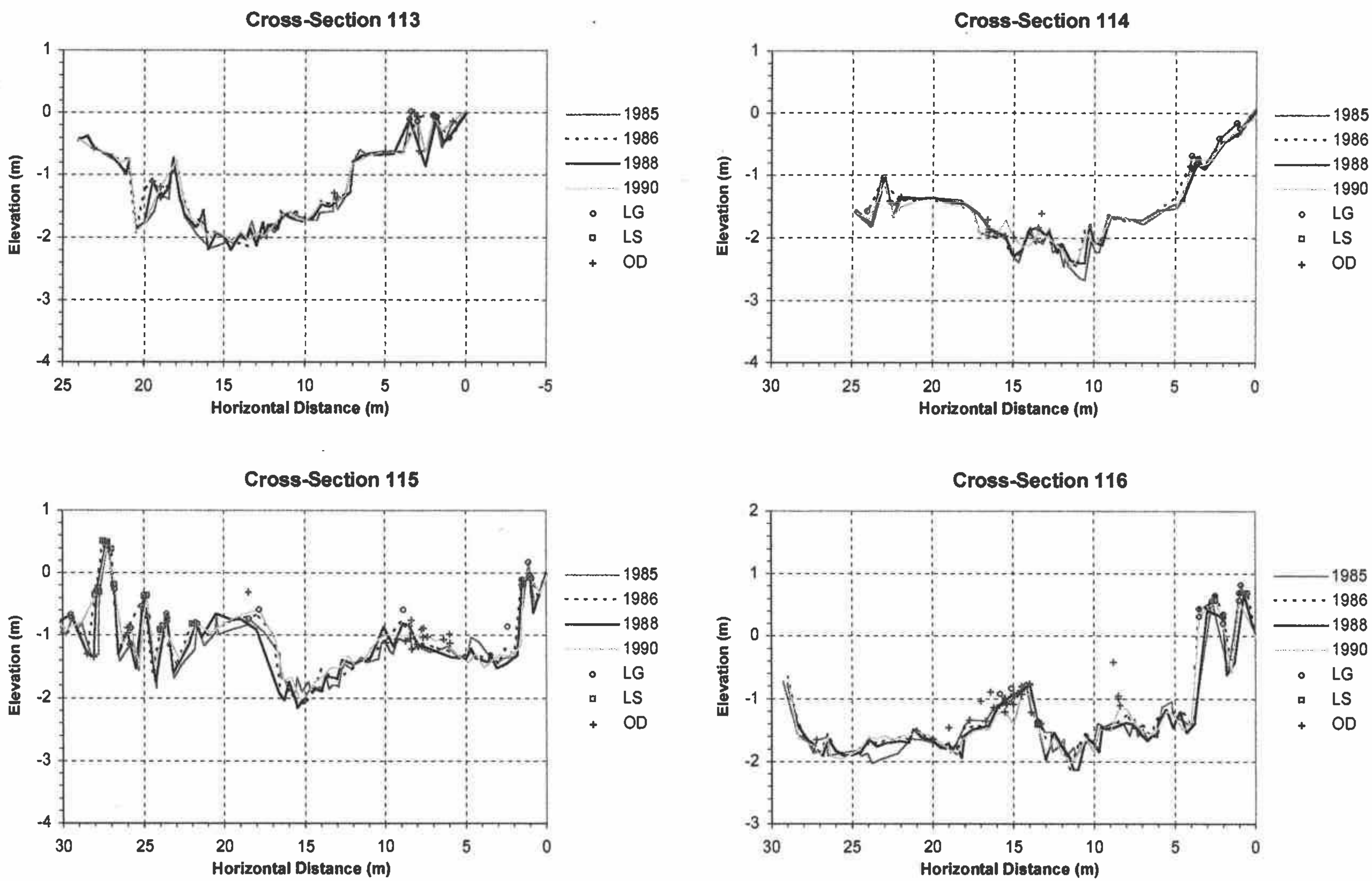


Figure B.13. (continued)

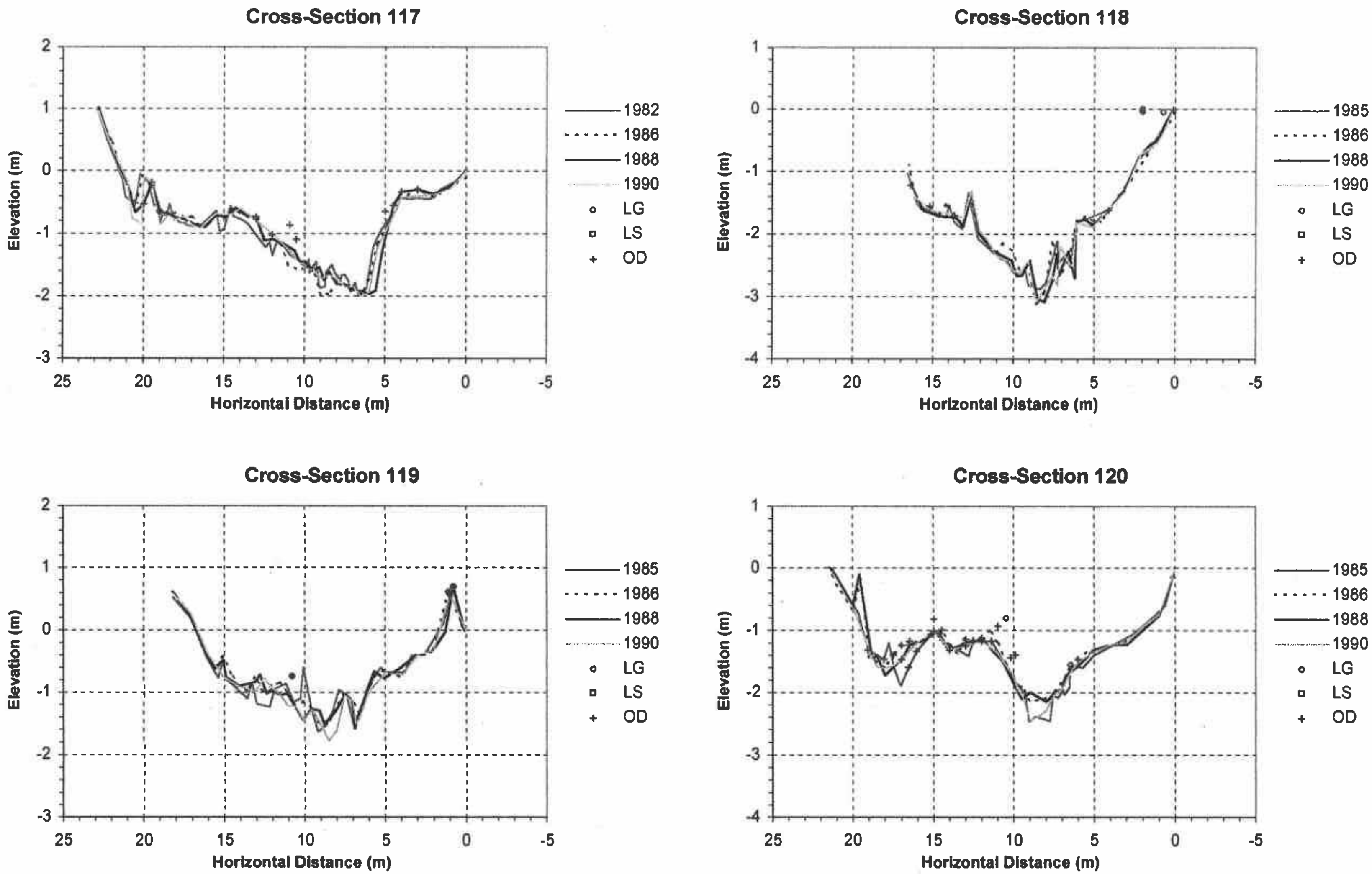


Figure B.13. (continued)

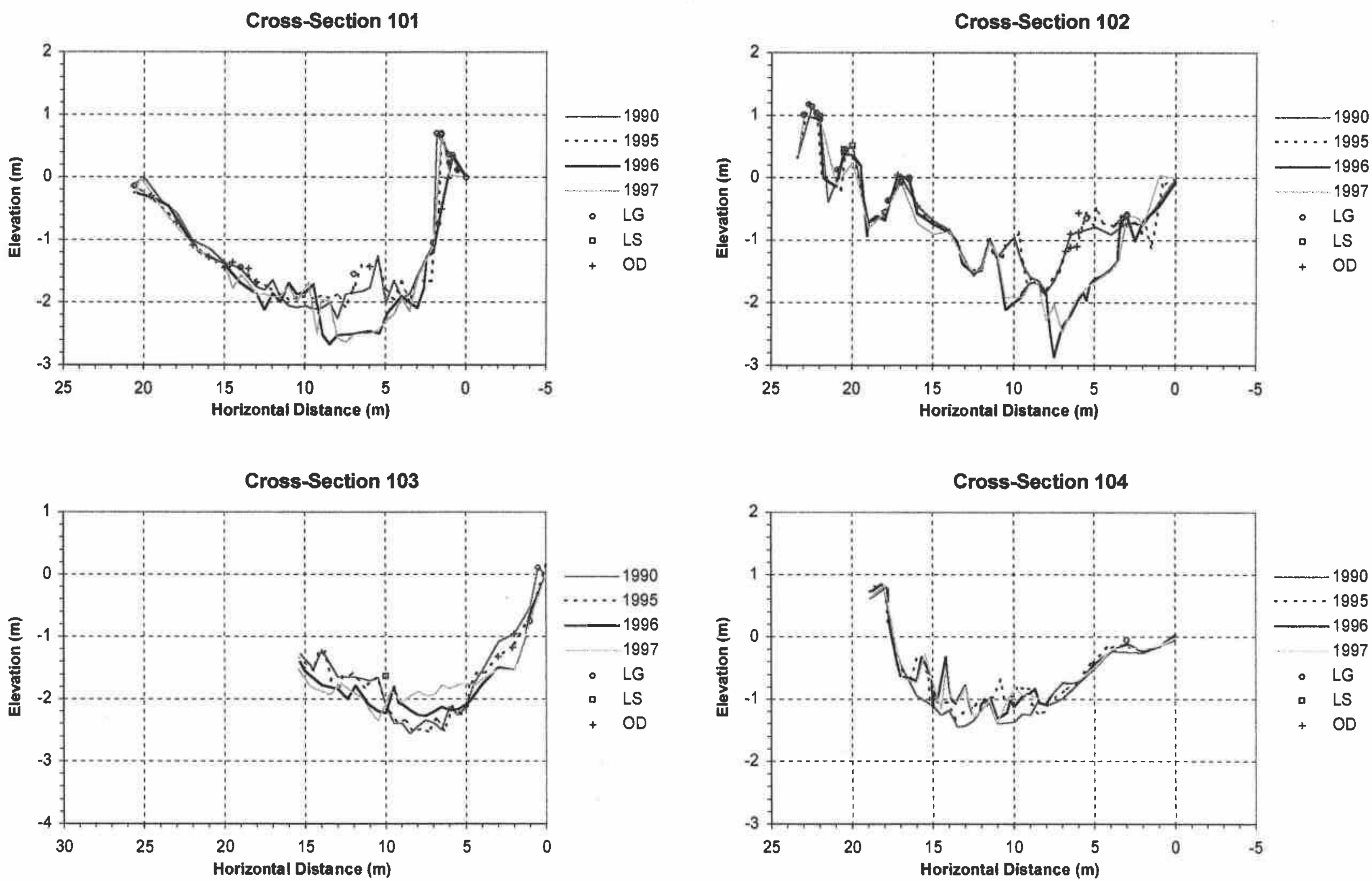
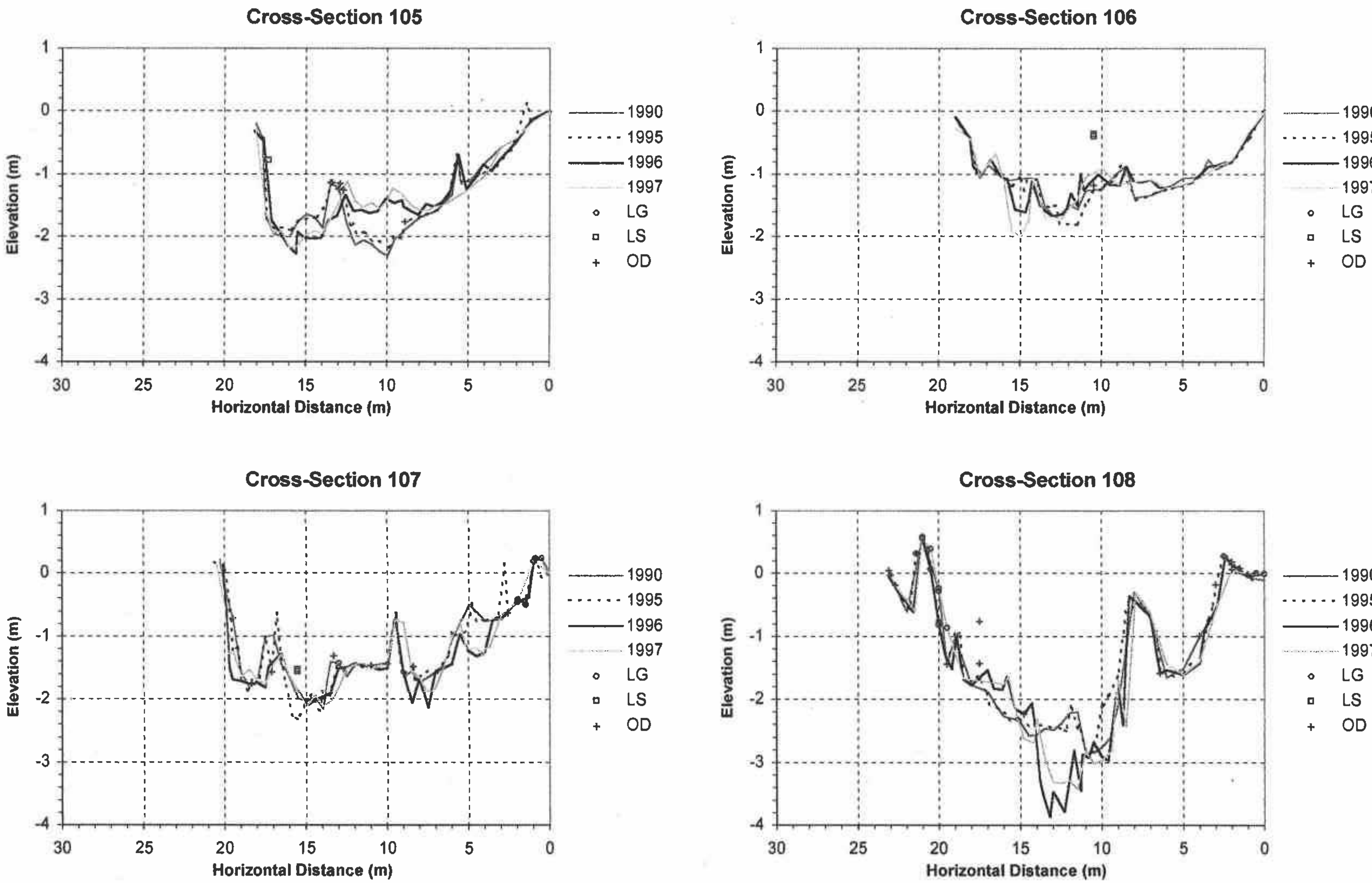


Figure B.14. Filtered cross section profile plots for Mack Creek Clearcut (MCC) site, 1990-97.



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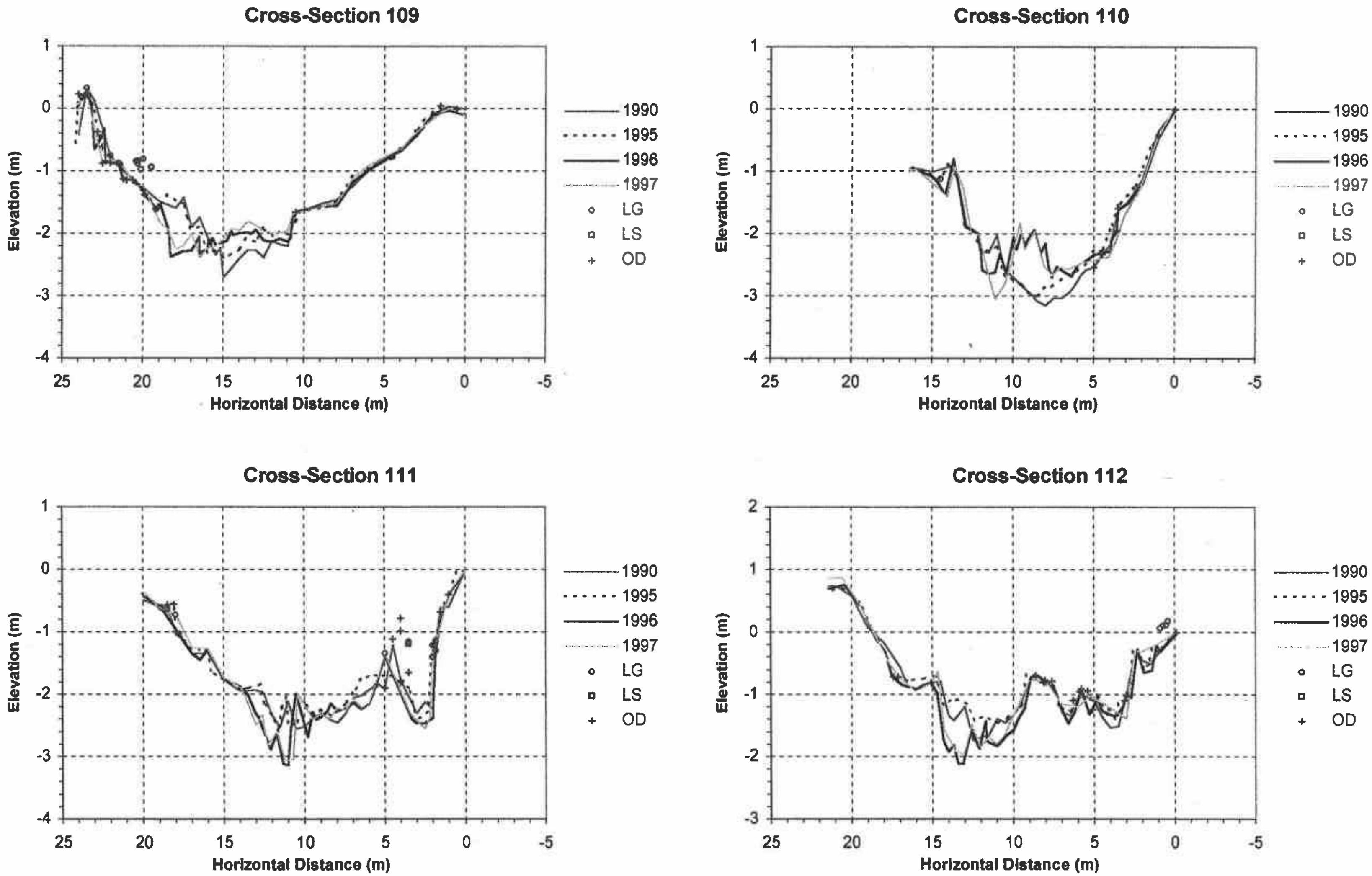

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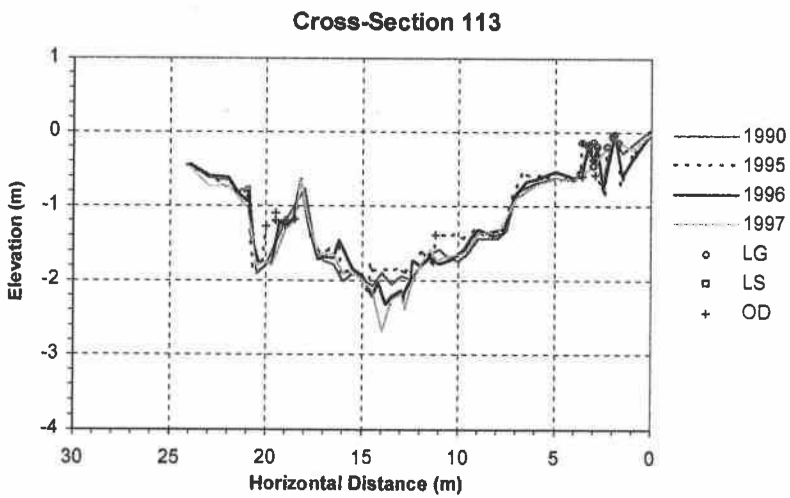
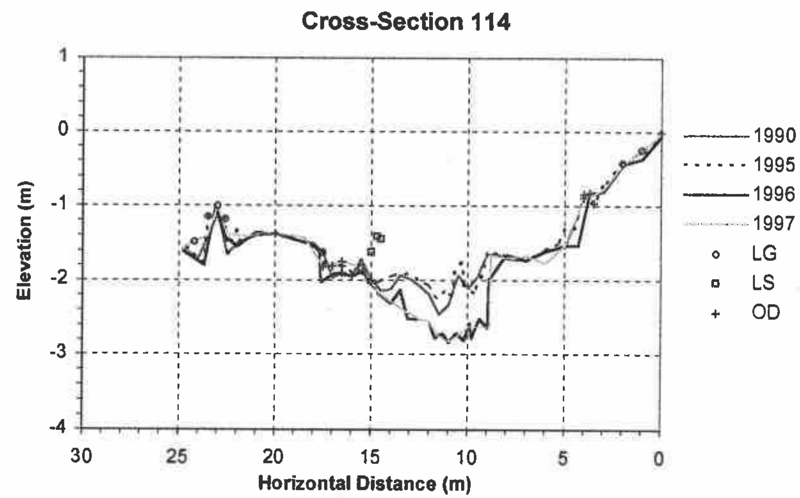
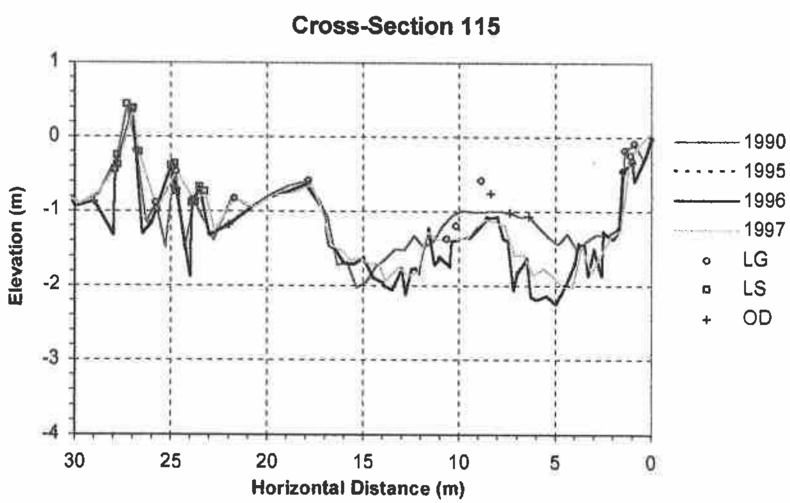






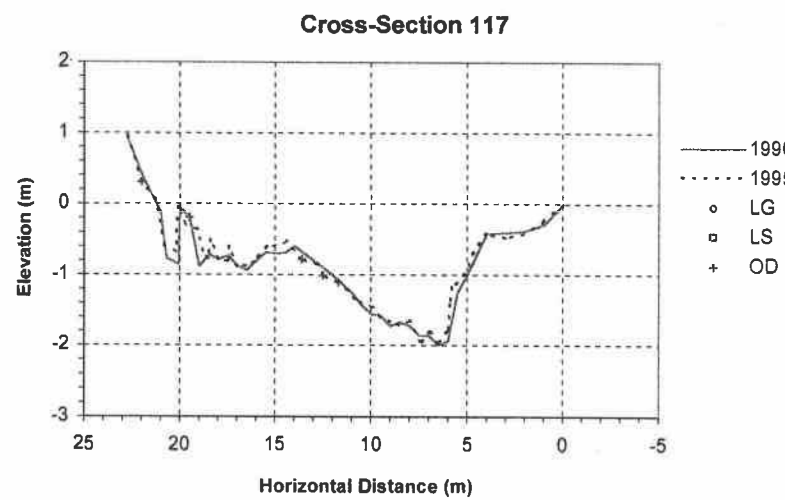
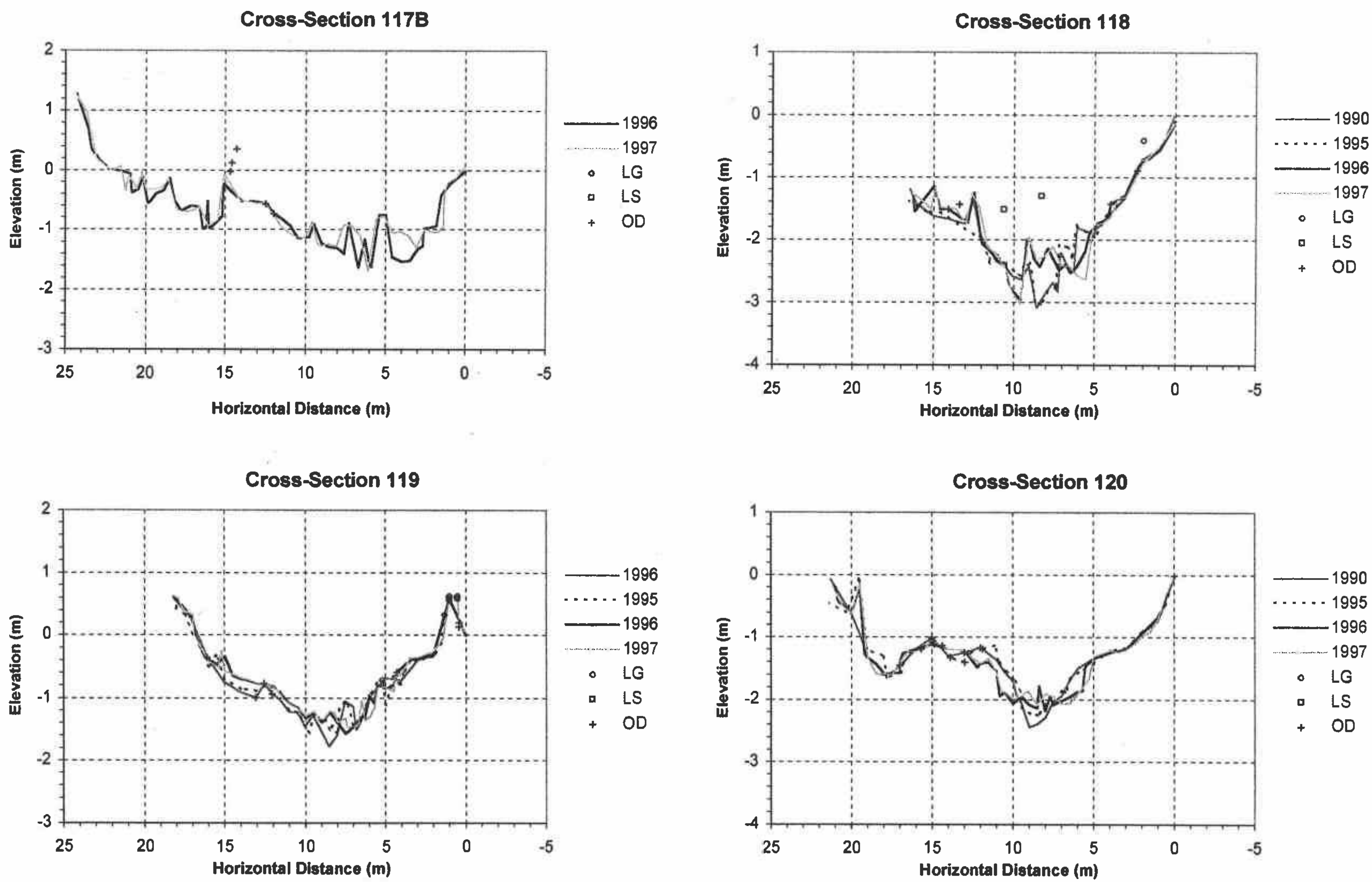


Figure B.14. (continued)



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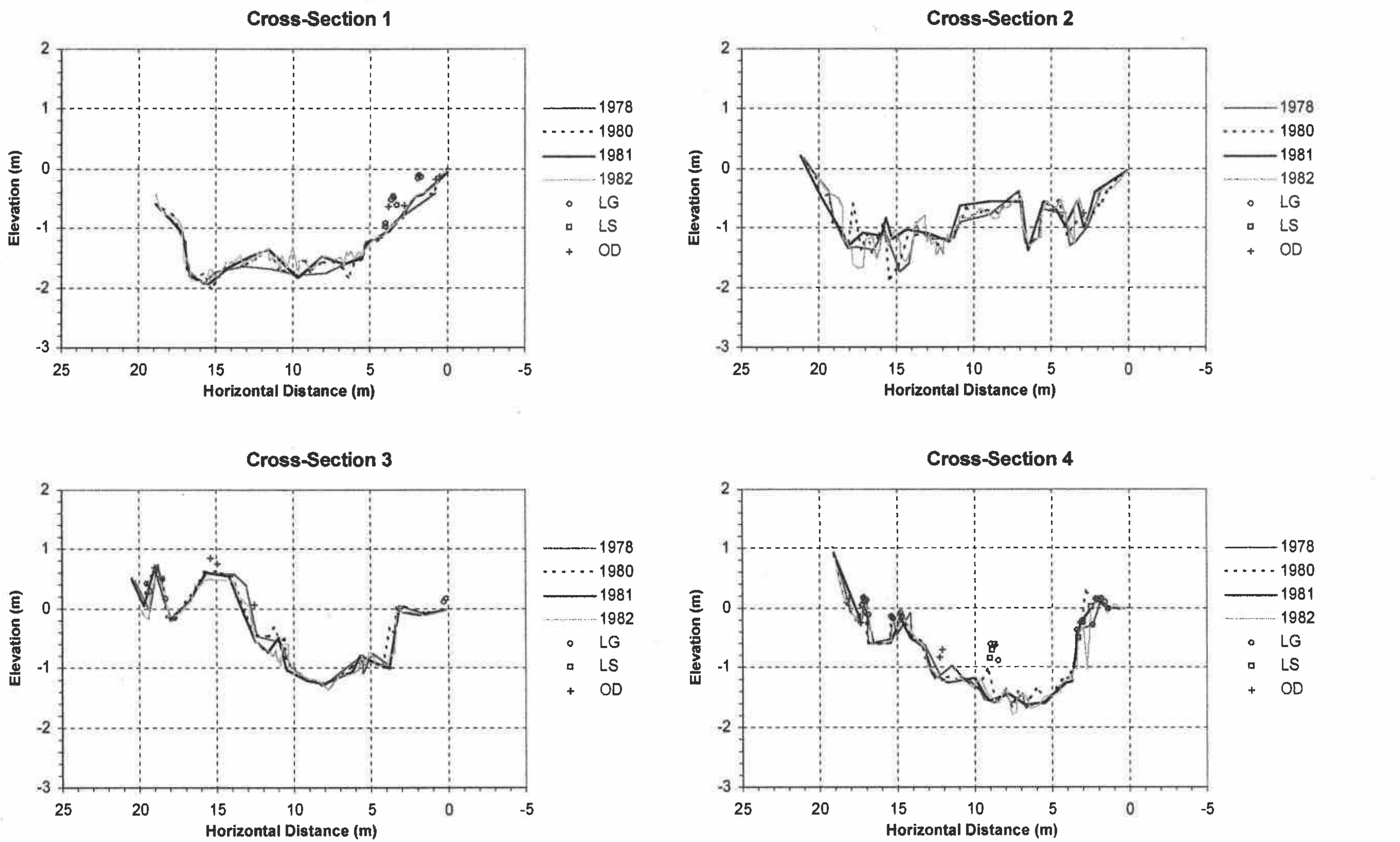


Figure B.15. Filtered cross section profile plots for Mack Creek old-growth (MAC) site, 1978-82.

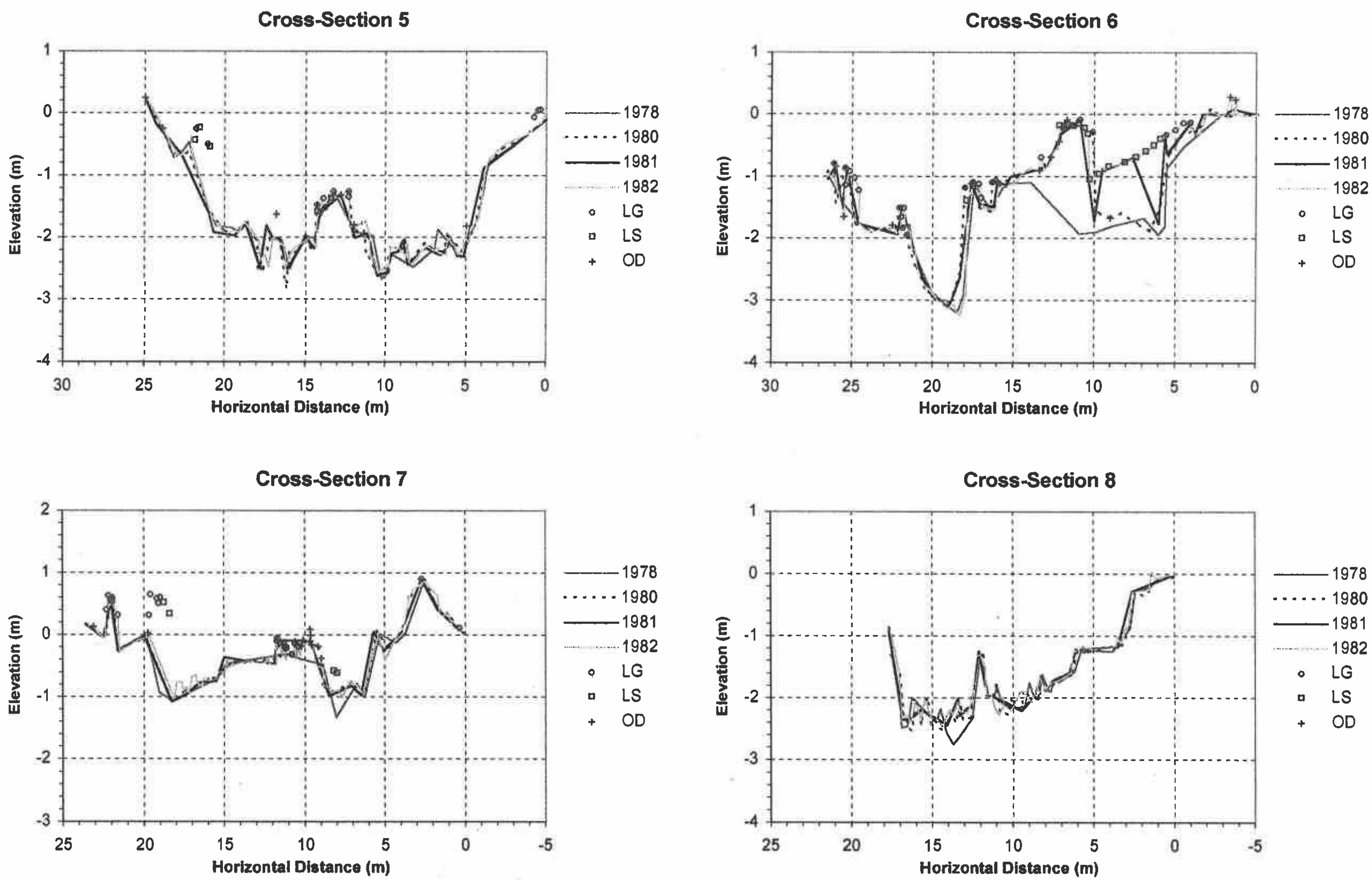


Figure B.15. (continued)

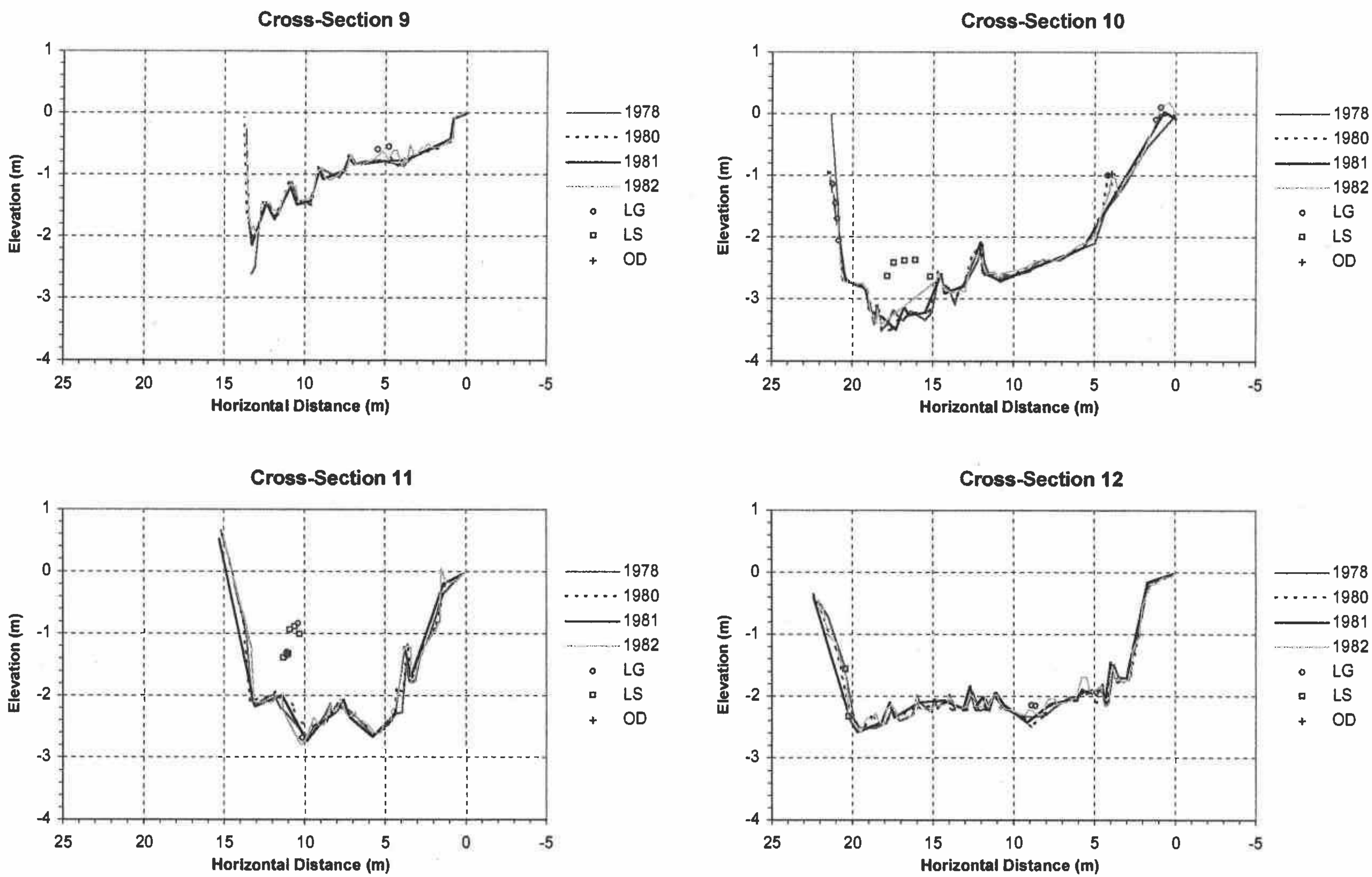


Figure B.15. (continued)

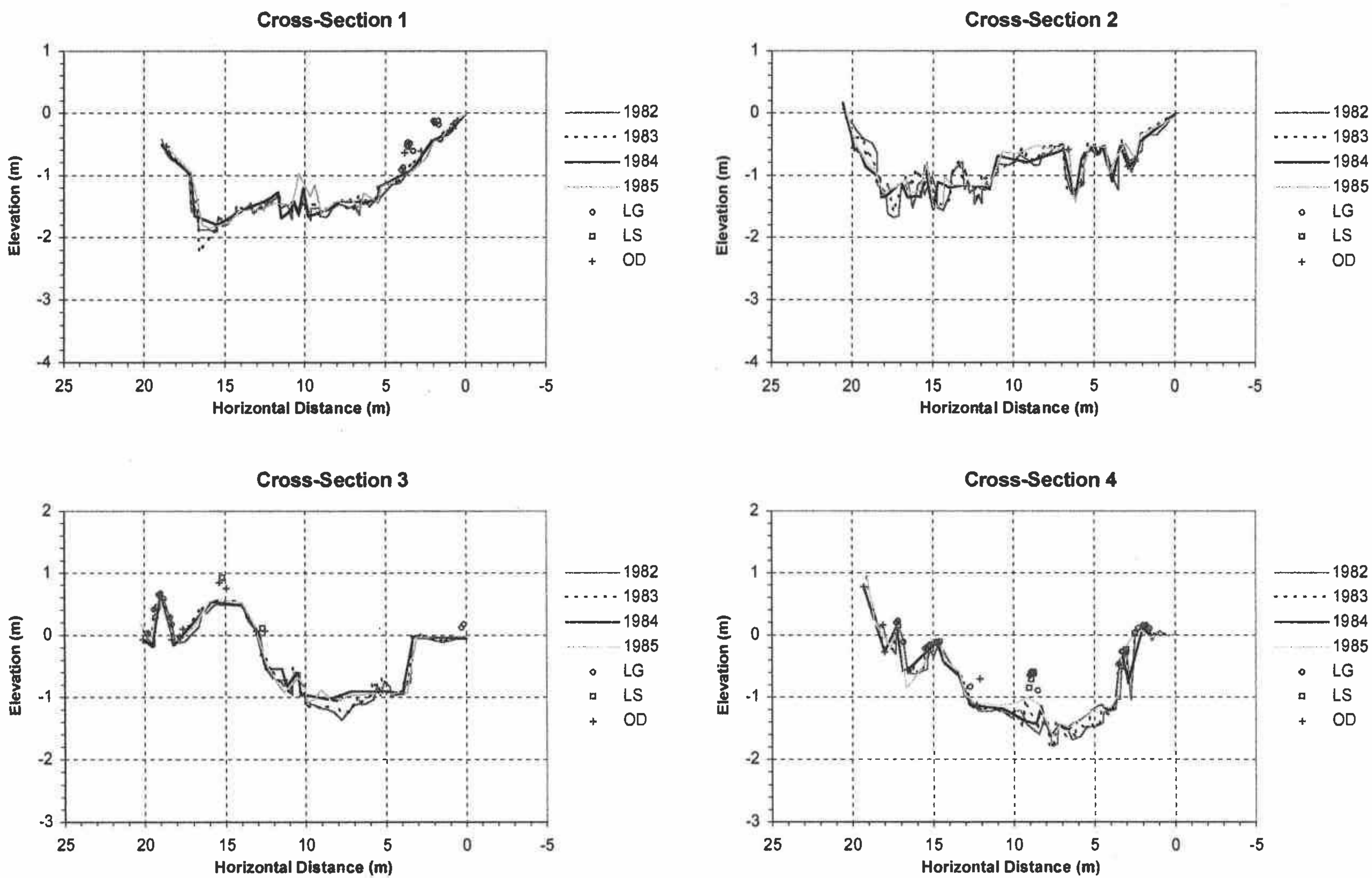


Figure B.16. Filtered cross section profile plots for Mack Creek old-growth (MAC) site, 1982-85.

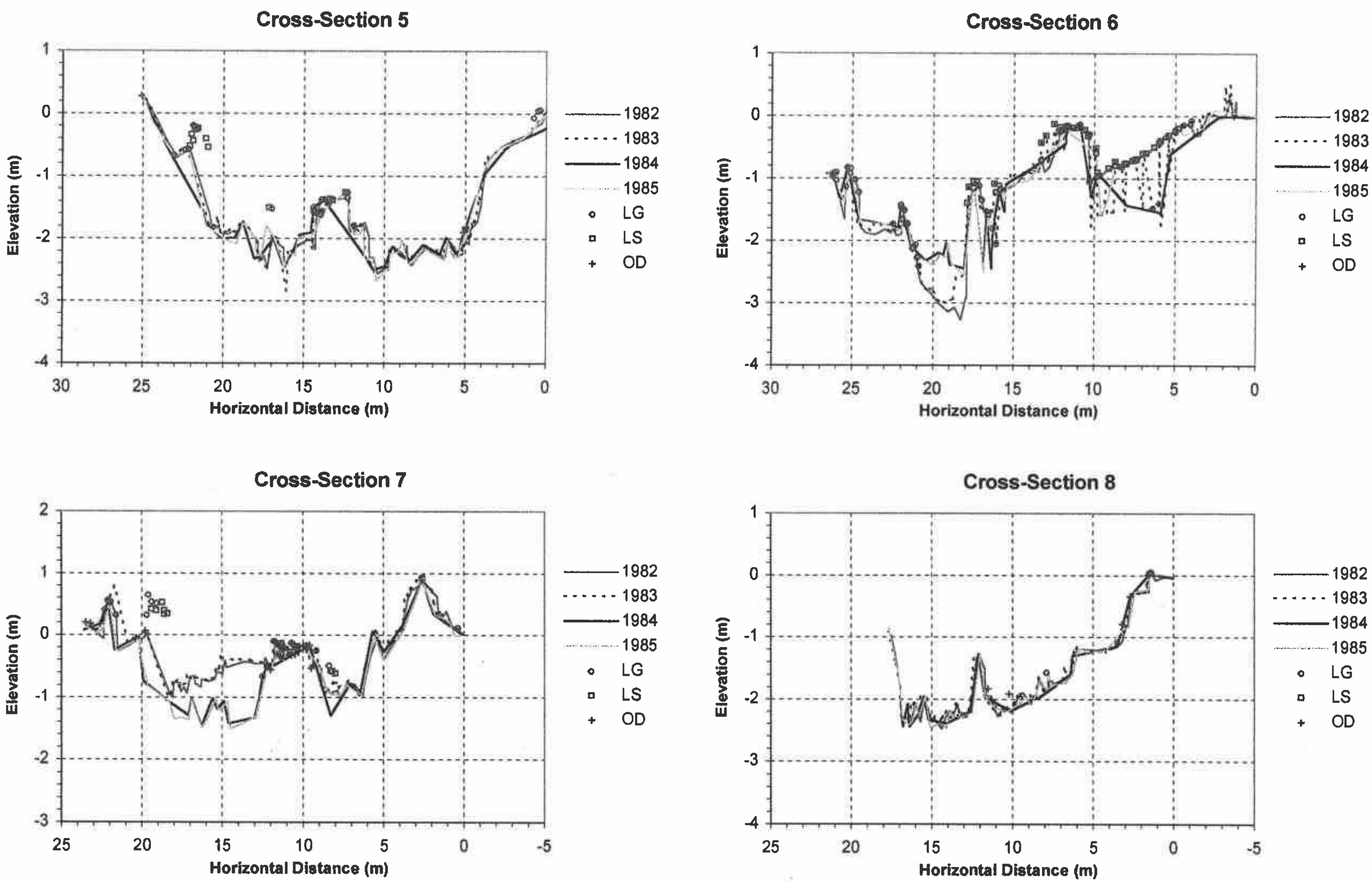
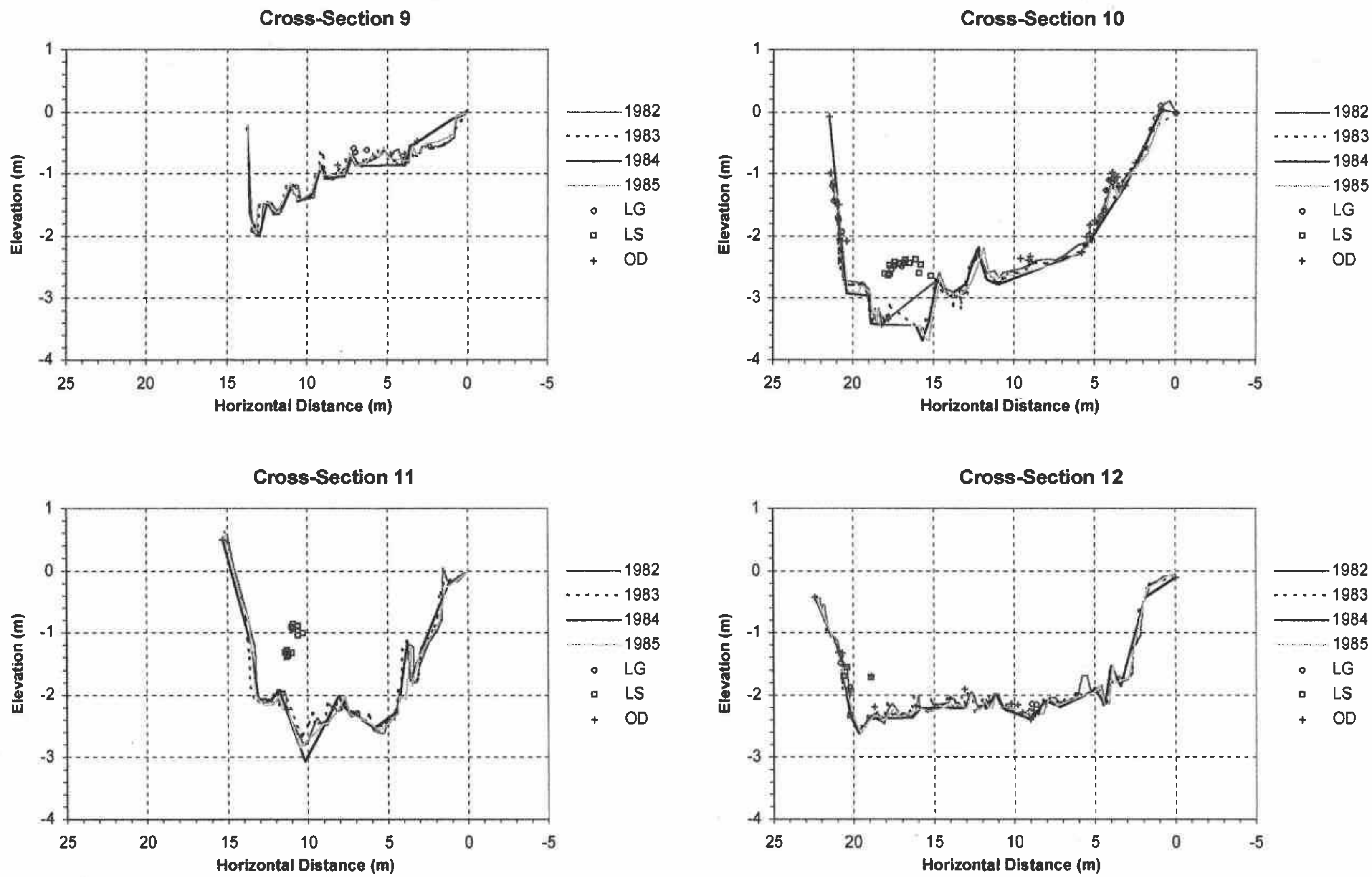


Figure B.16. (continued)



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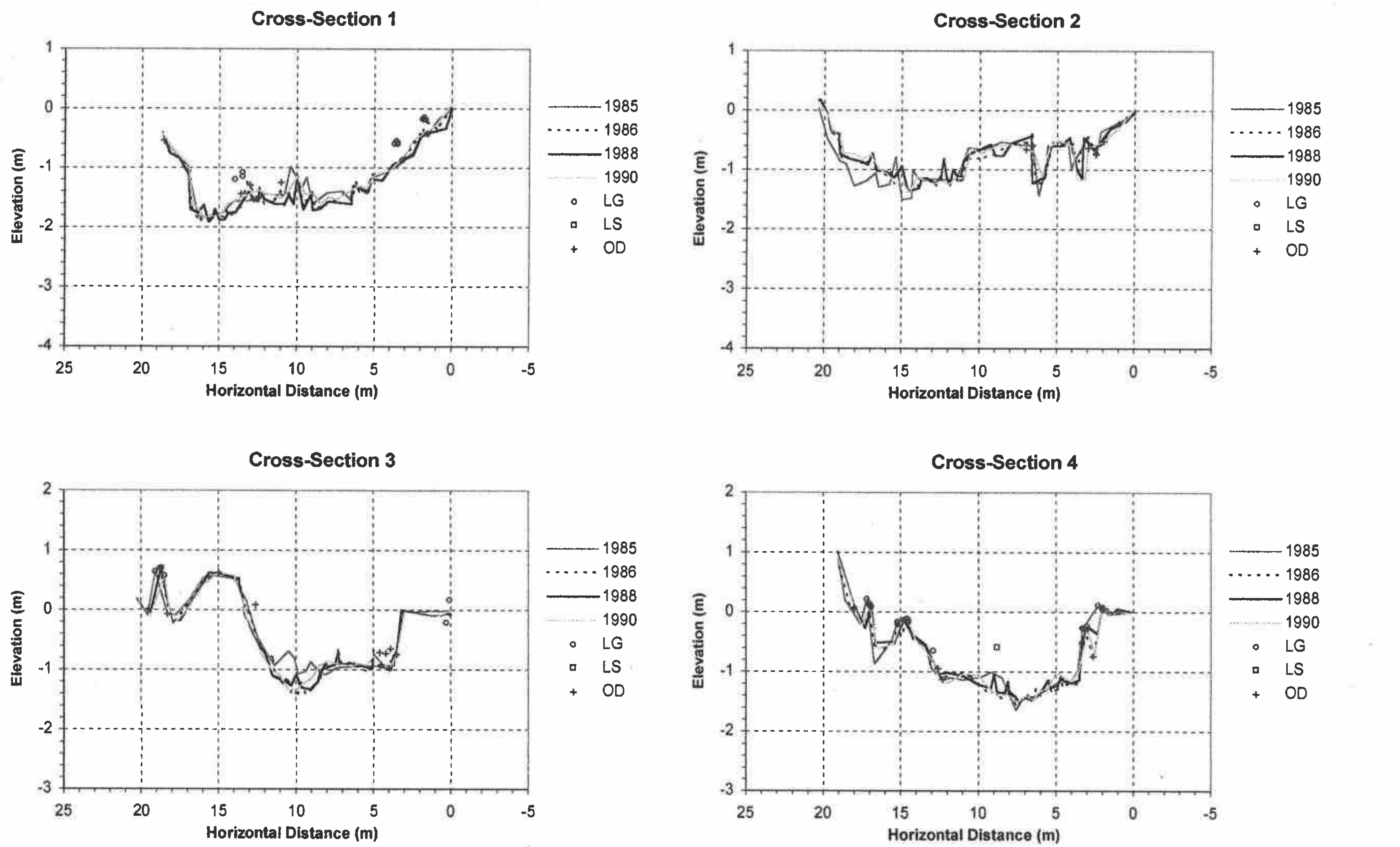
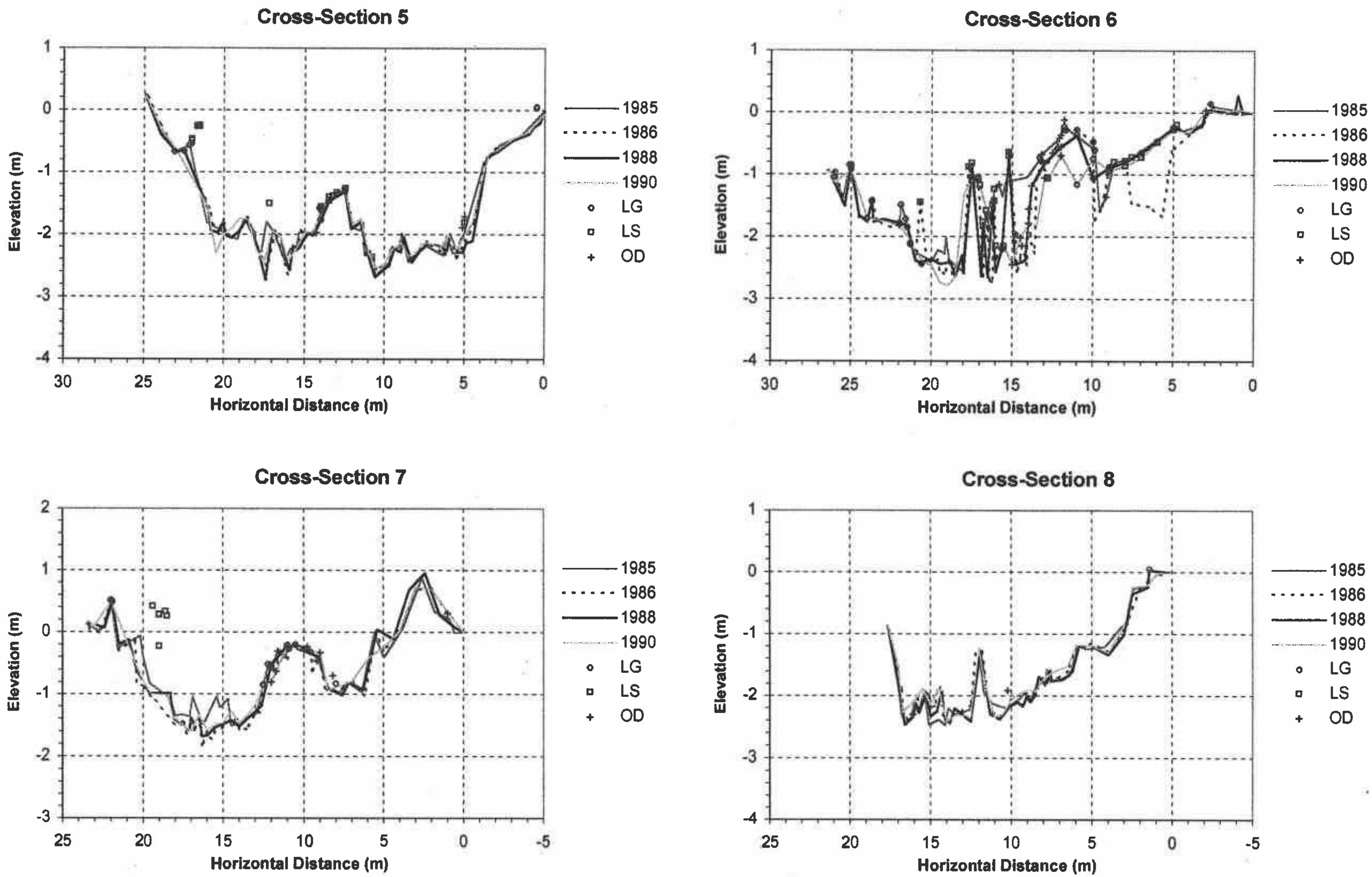


Figure B.17. Filtered cross section profile plots for Mack Creek old-growth (MAC) site, 1985-90.



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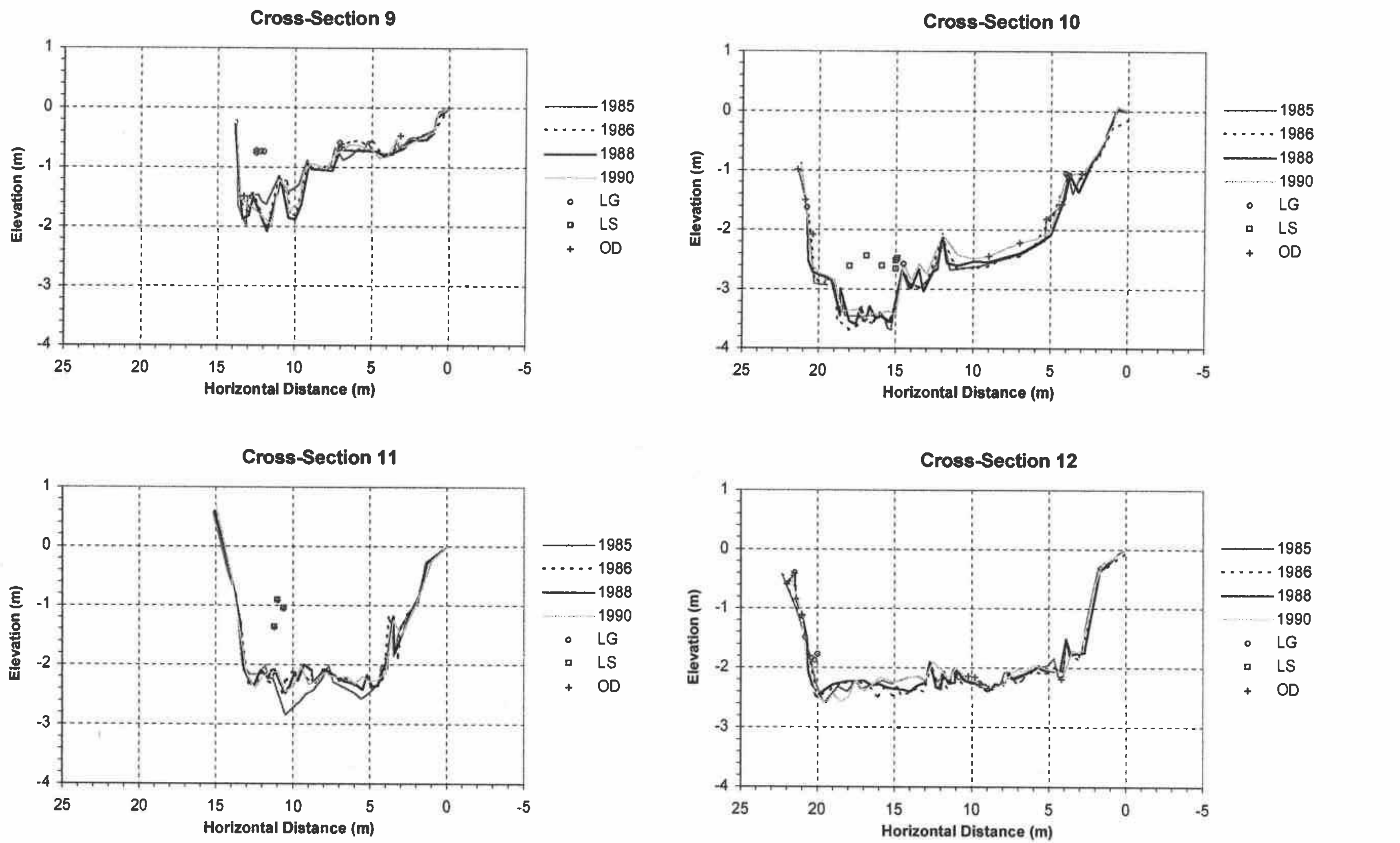

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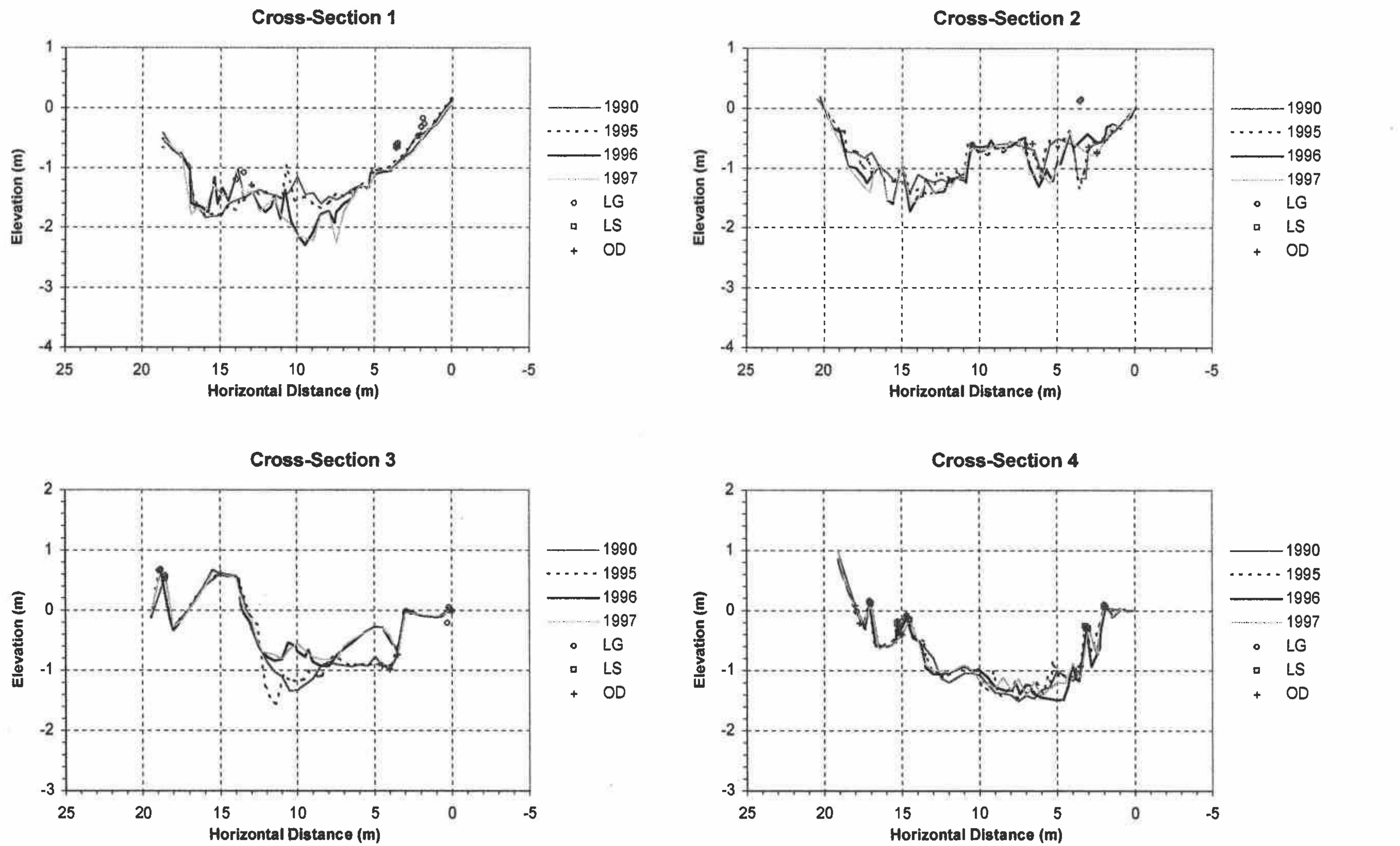

Figure B.18. Filtered cross section profile plots for Mack Creek old-growth (MAC) site, 1990-97.

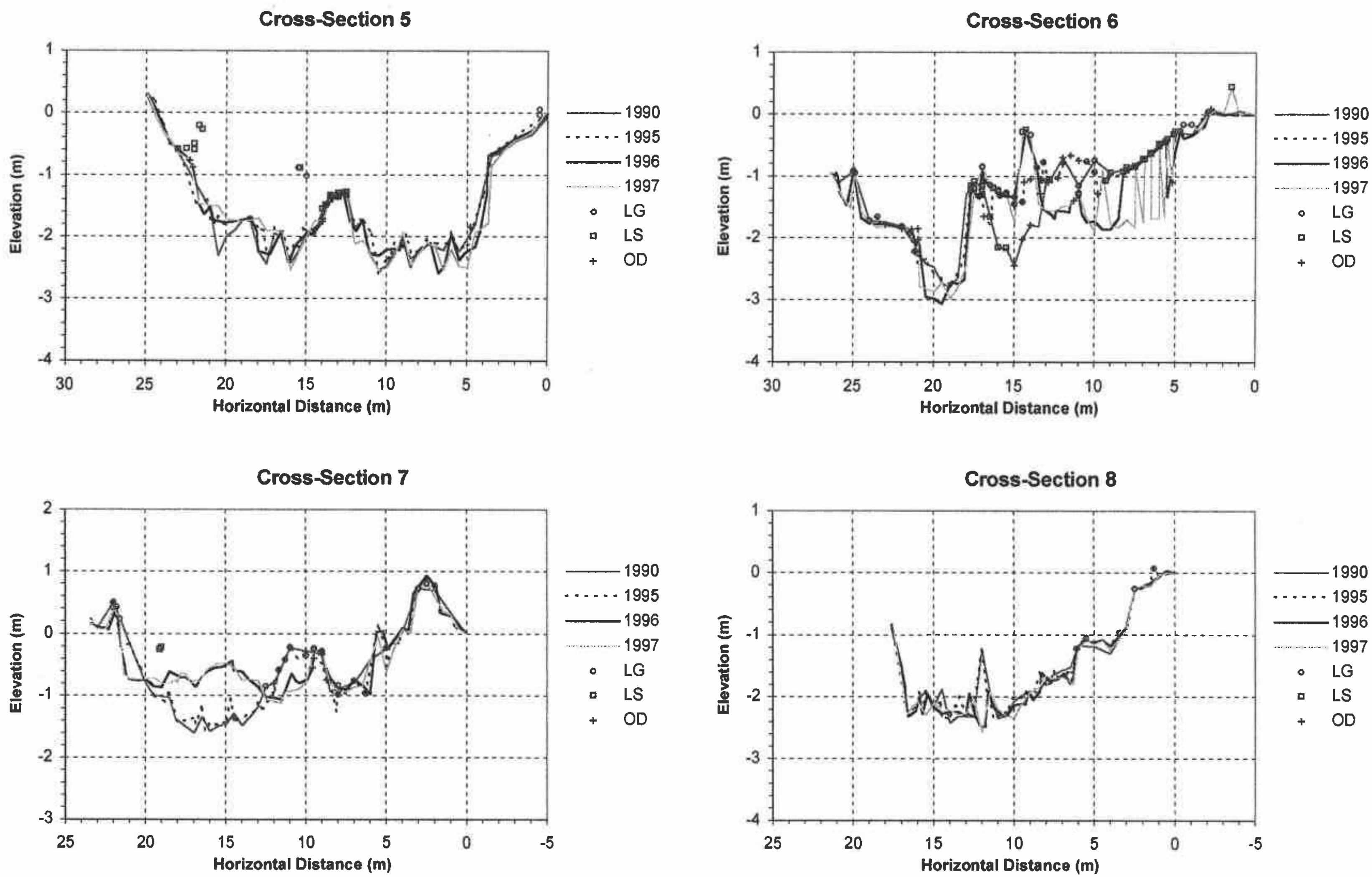

Figure B.18. (continued)

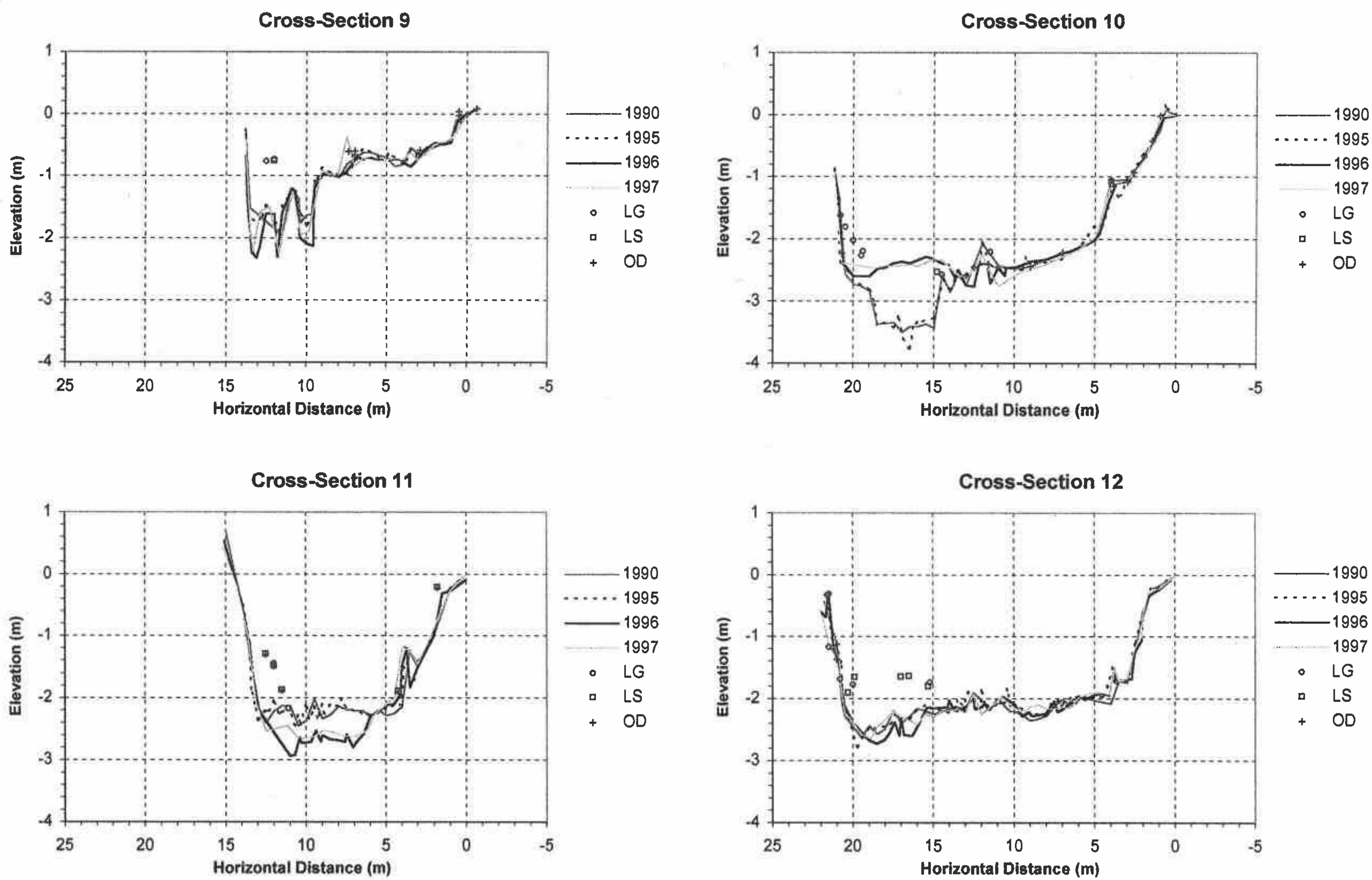

Figure B.18. (continued)

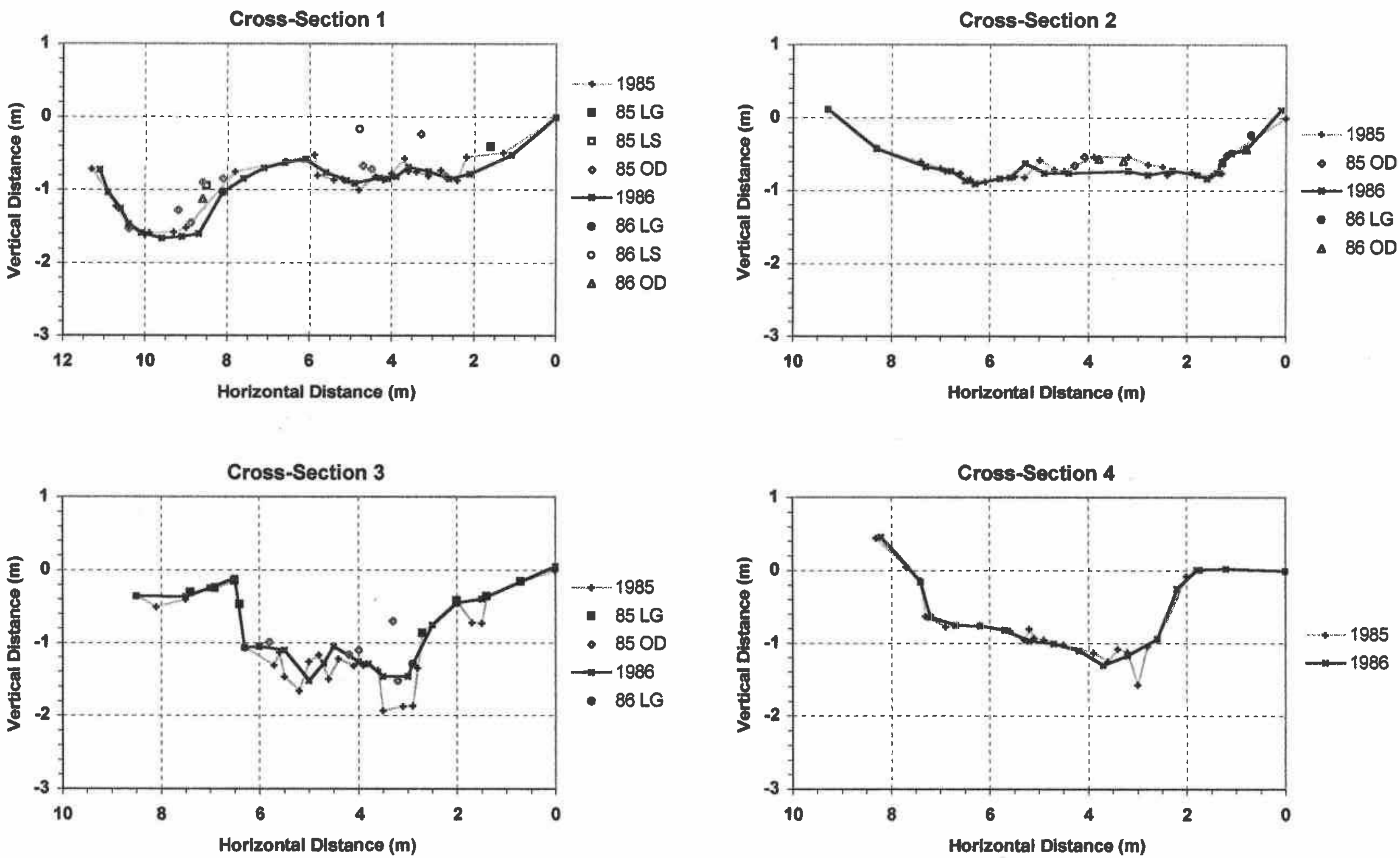

Figure B.19. Filtered cross section profile plots for Cold Creek (COC) site, 1985-86.

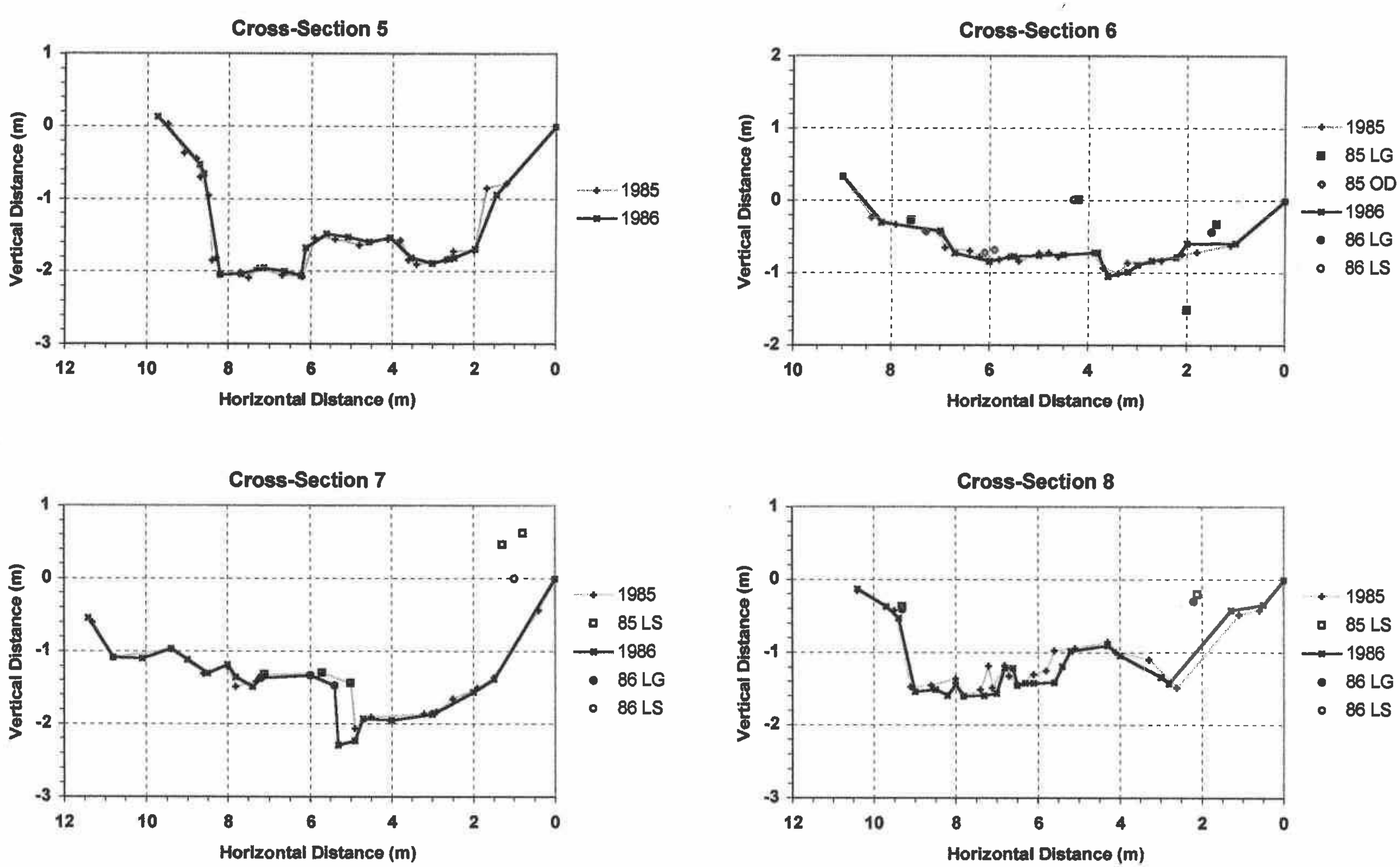

Figure B.19. (continued)

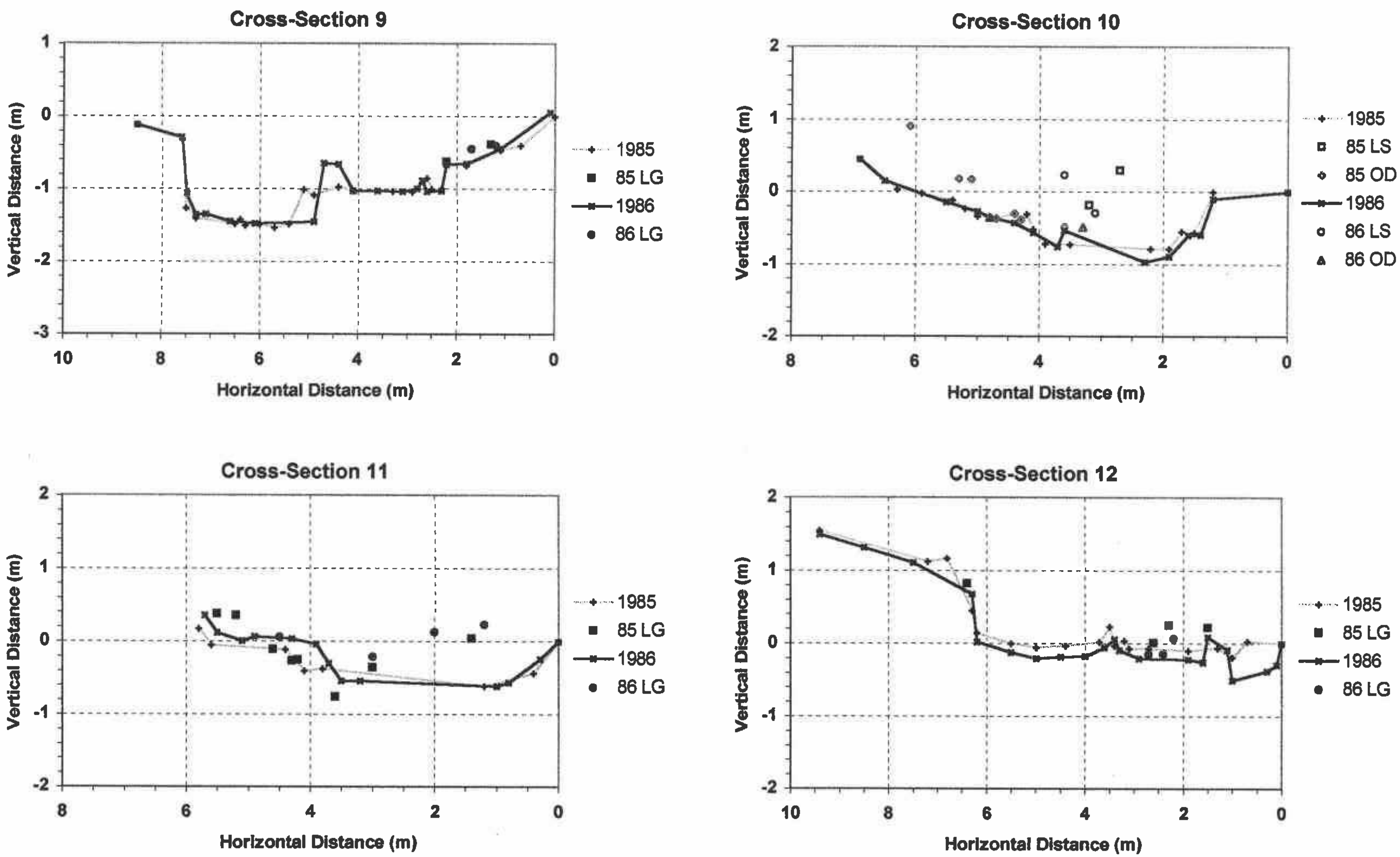

Figure B.19. (continued)

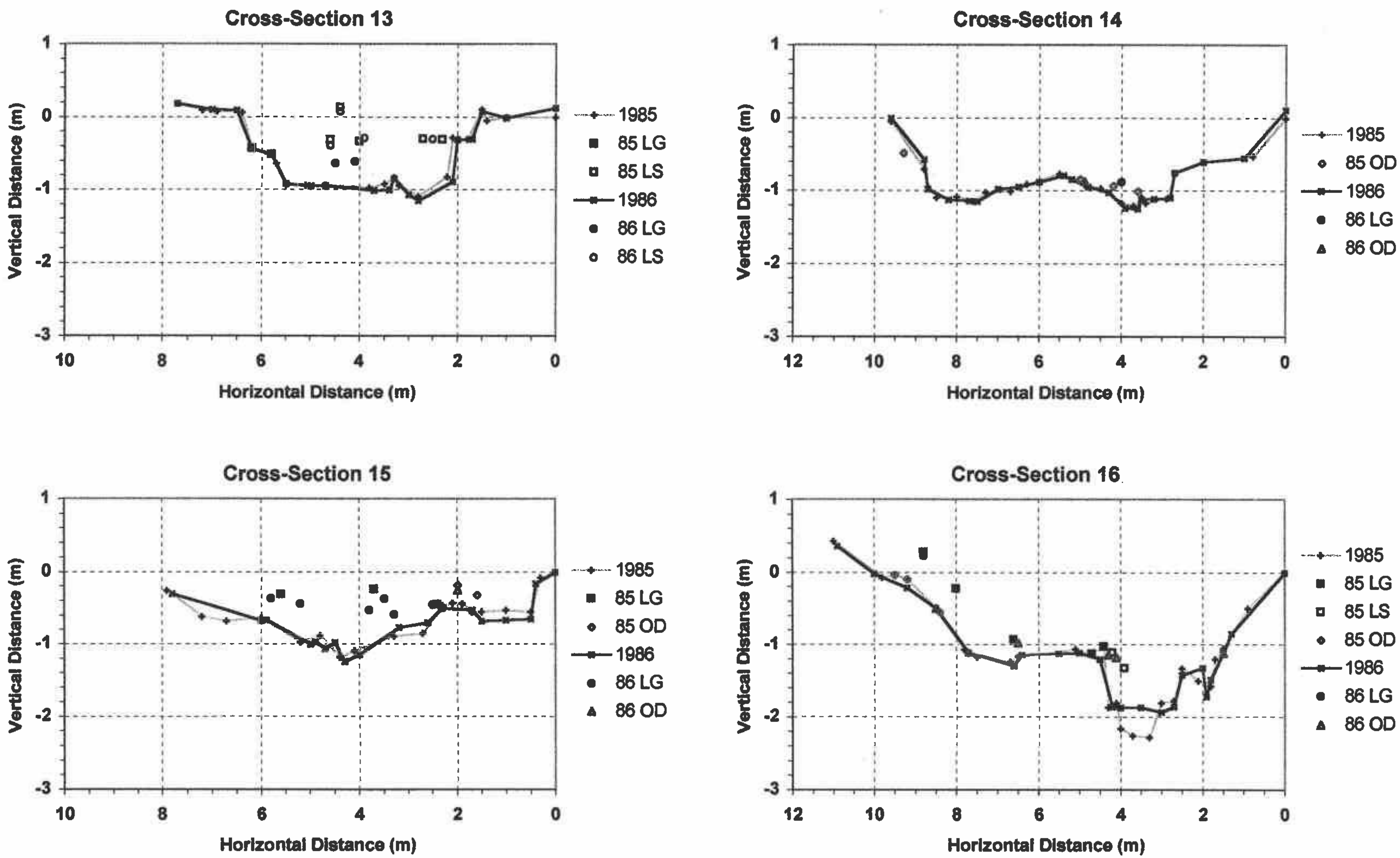

Figure B.19. (continued)

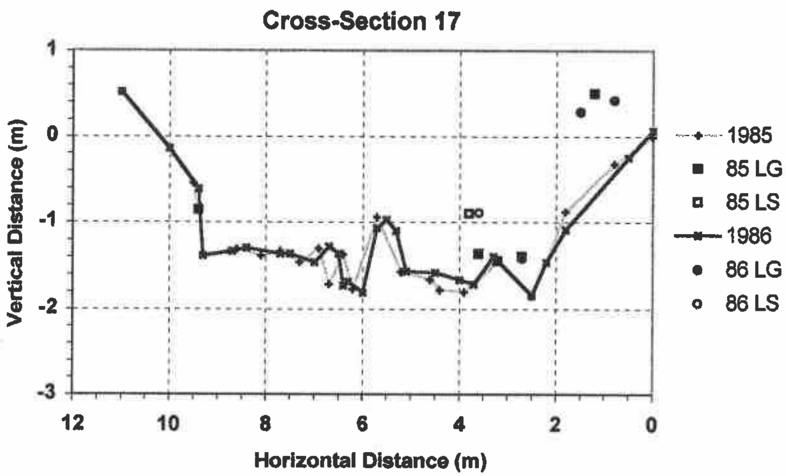

Figure B.19. (continued)

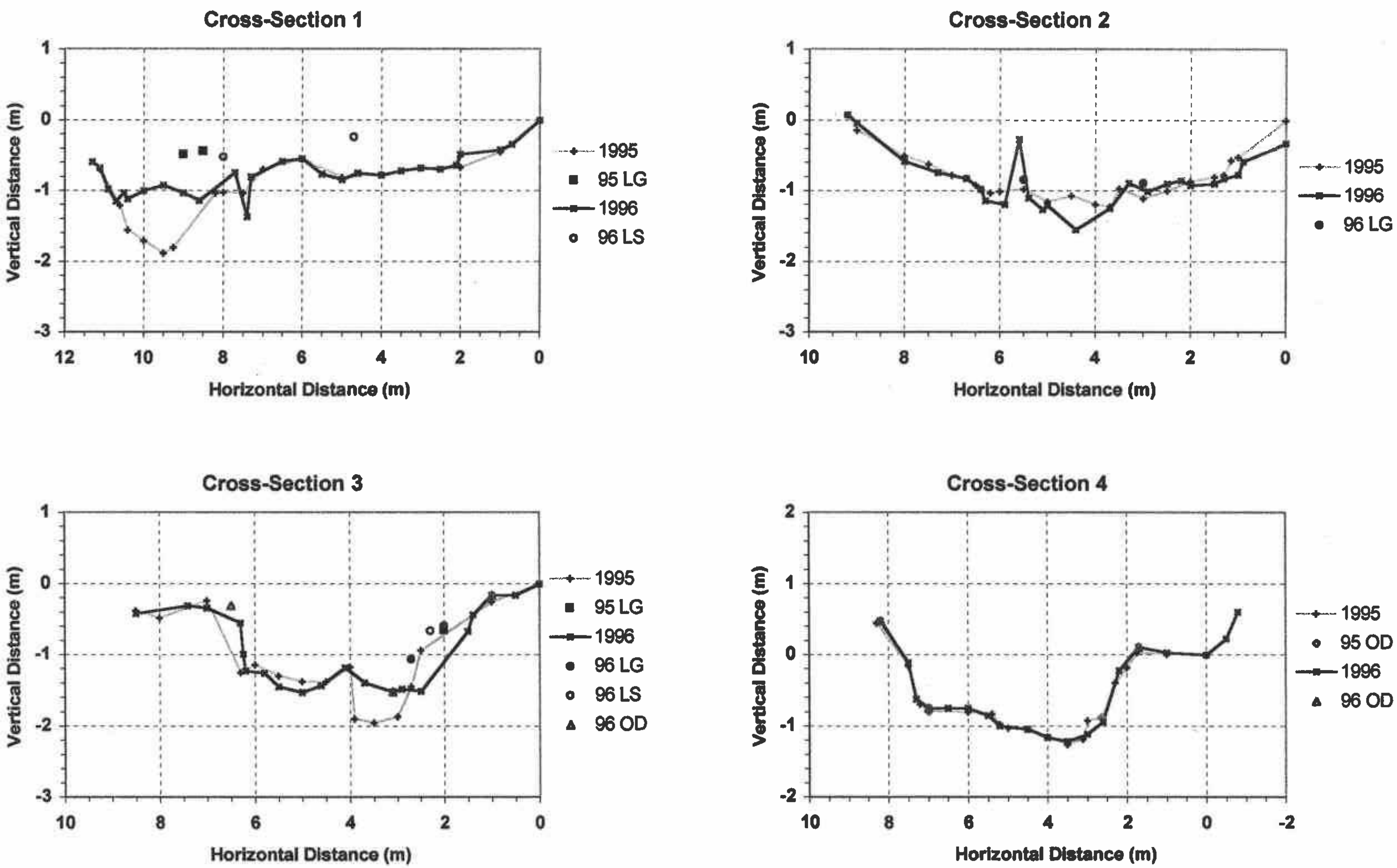

Figure B.20. Filtered cross section profile plots for Cold Creek (COC) site, 1995-96.

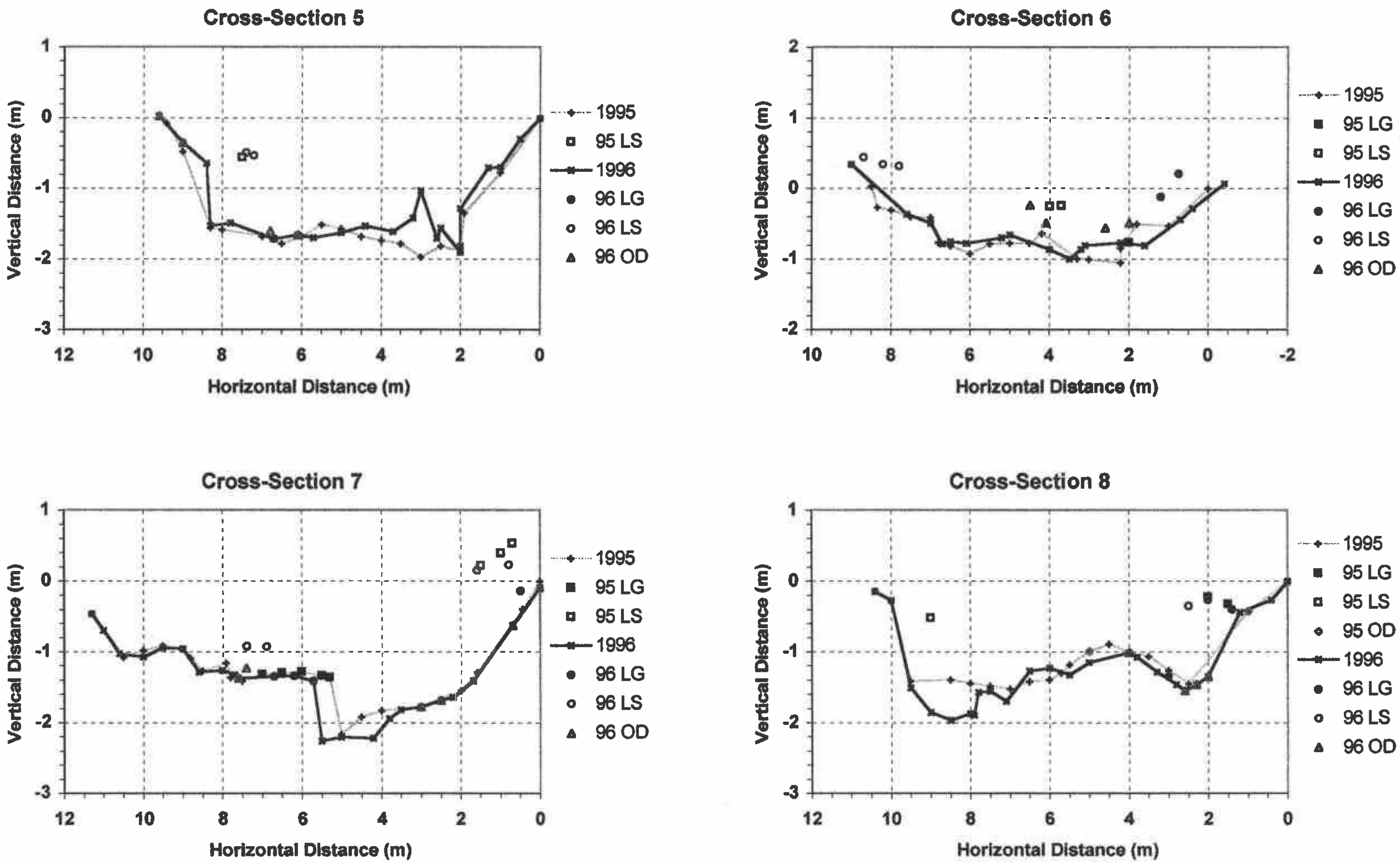

Figure B.20. (continued)

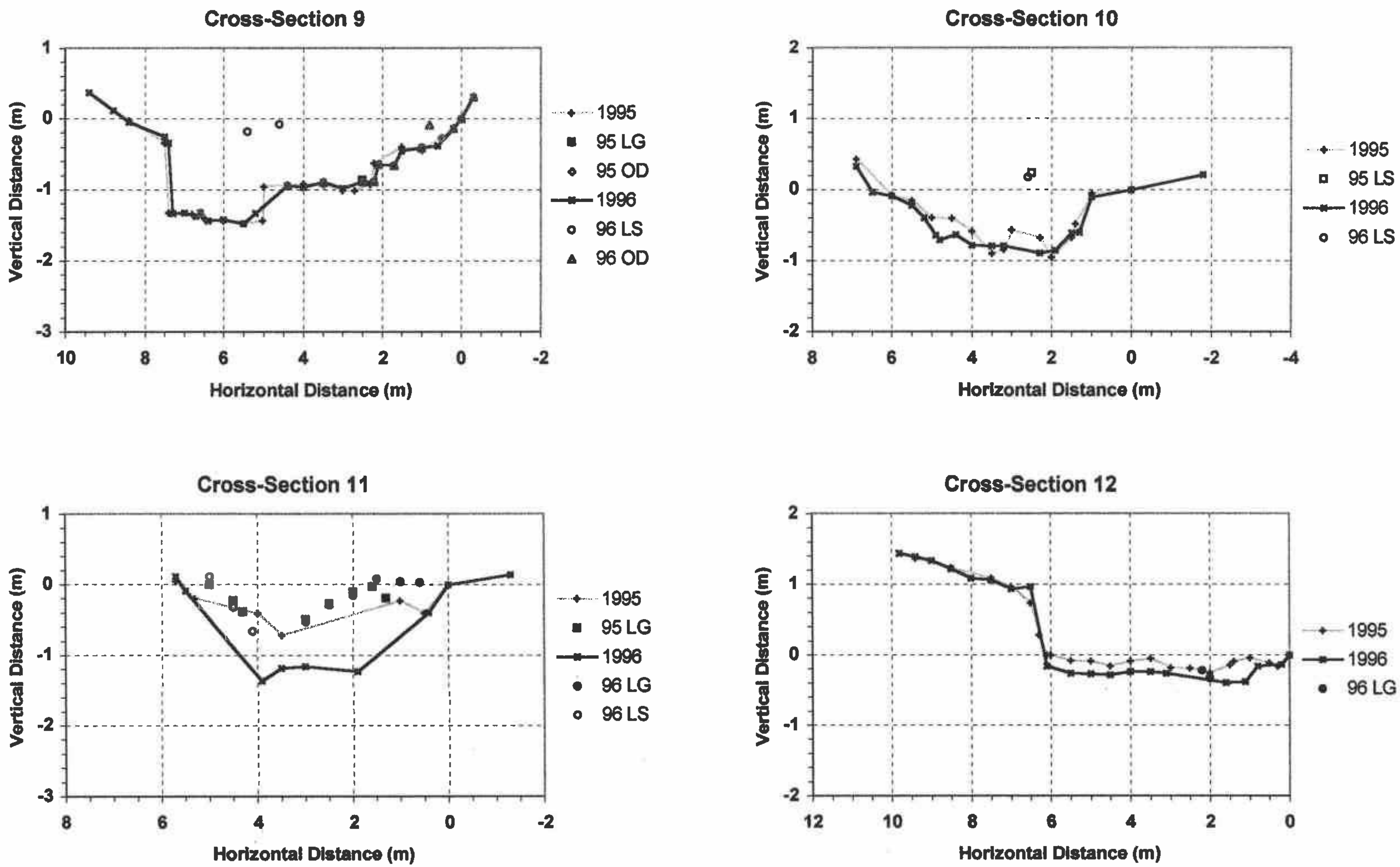

Figure B.20. (continued)

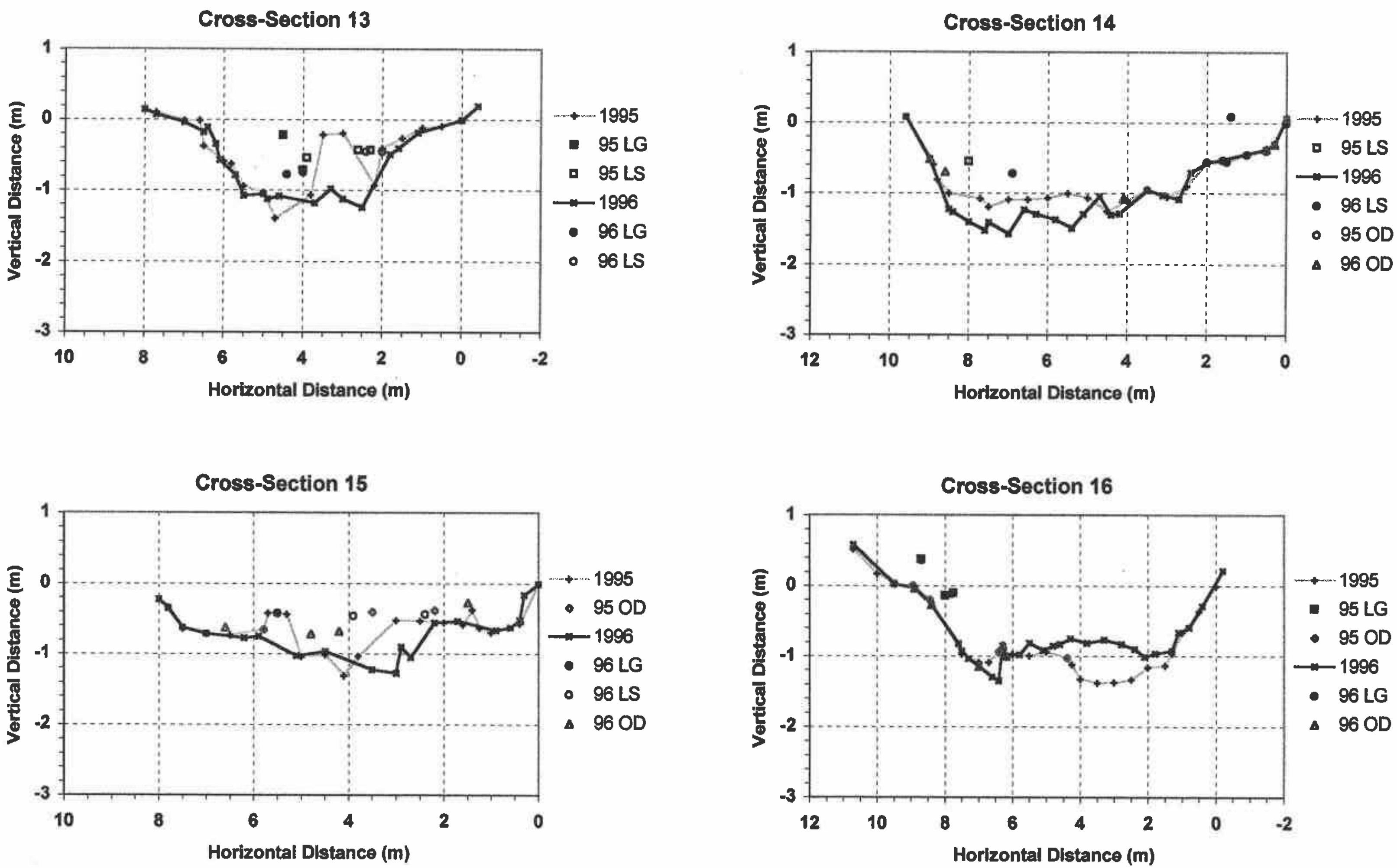

Figure B.20. (continued)

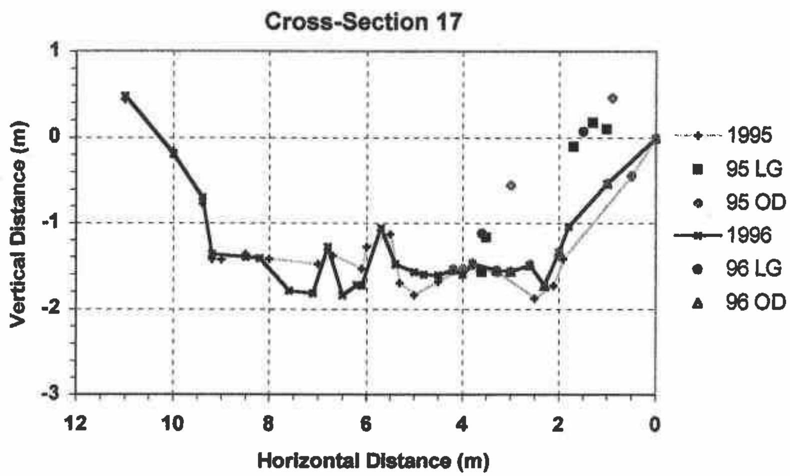

Figure B.20. (continued)

Appendix C

Channel Maps for Cold Creek Site

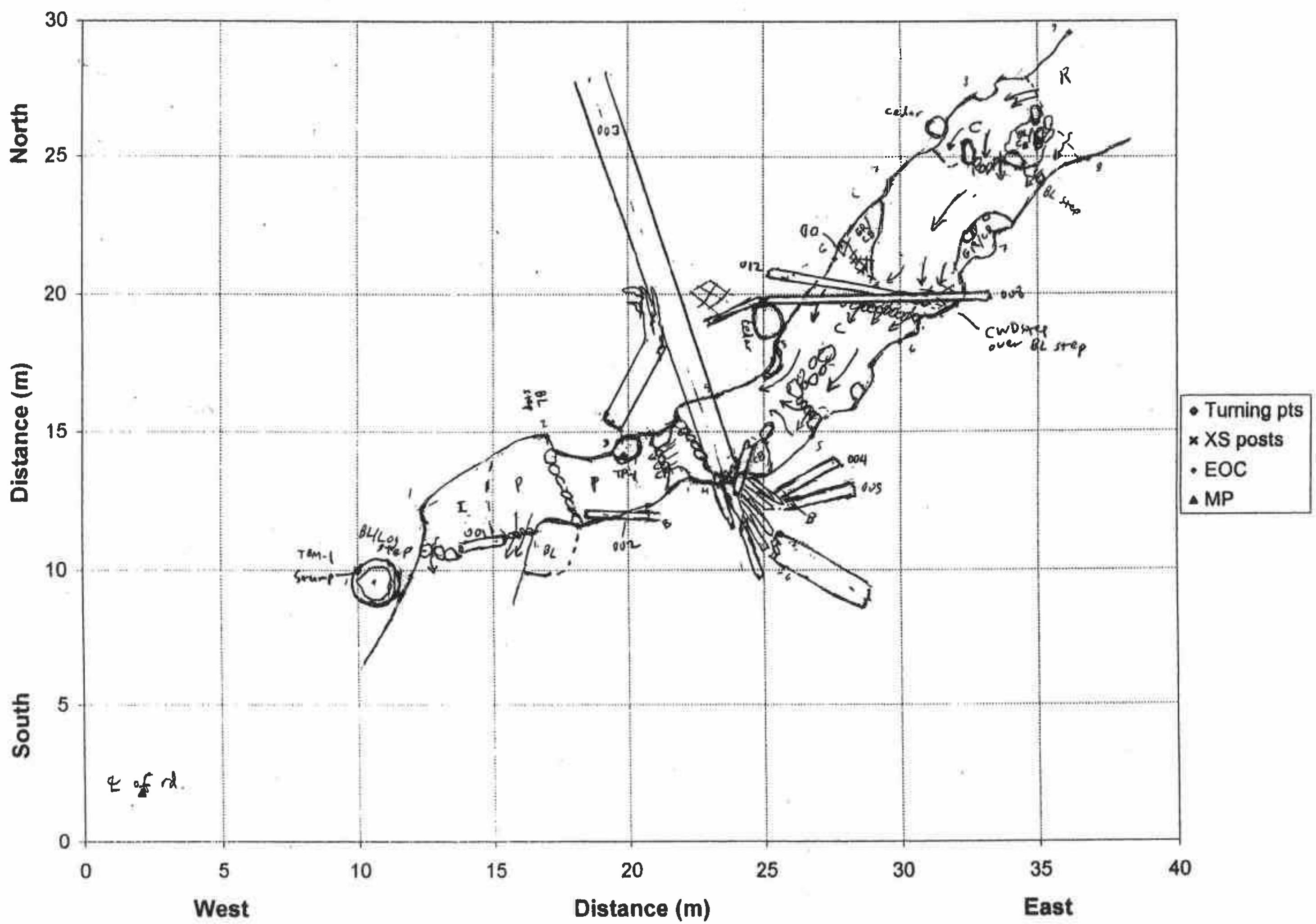

Figure C.1. Map of Cold Creek (COC) site, summer 1998, segment A.

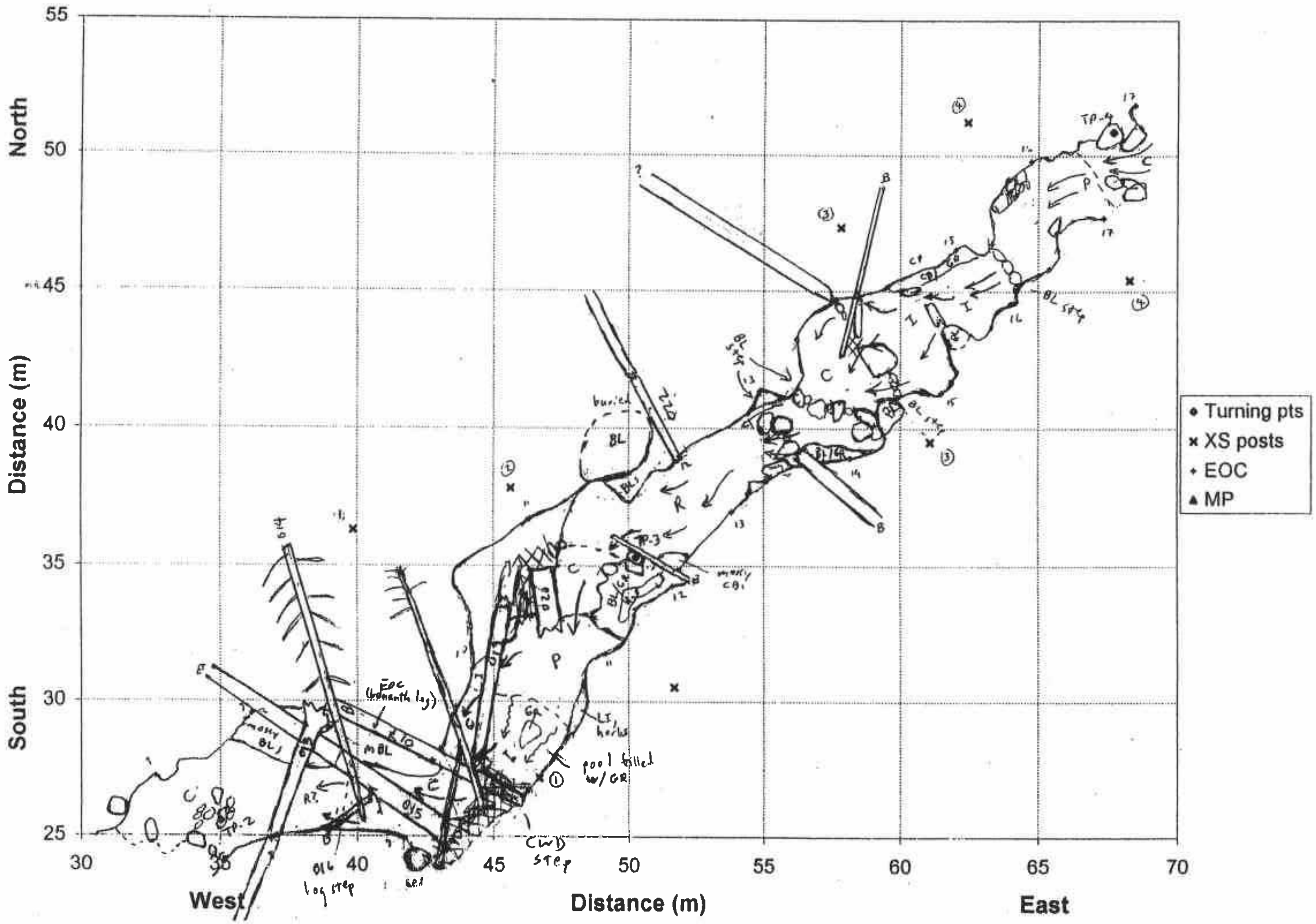

Figure C.2. Map of Cold Creek (COC) site, summer 1998, segment B.

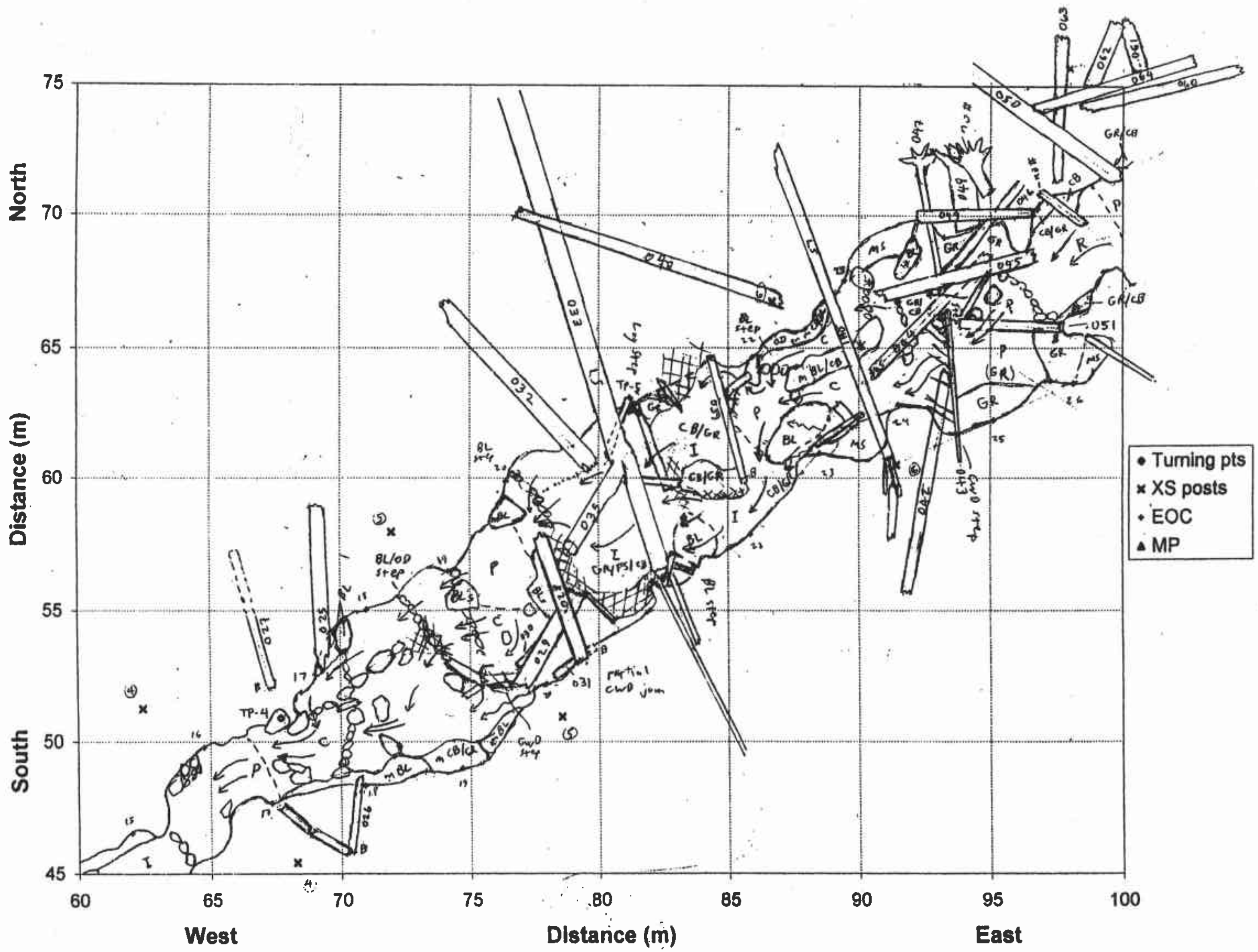

Figure C.3. Map of Cold Creek (COC) site, summer 1998, segment C.

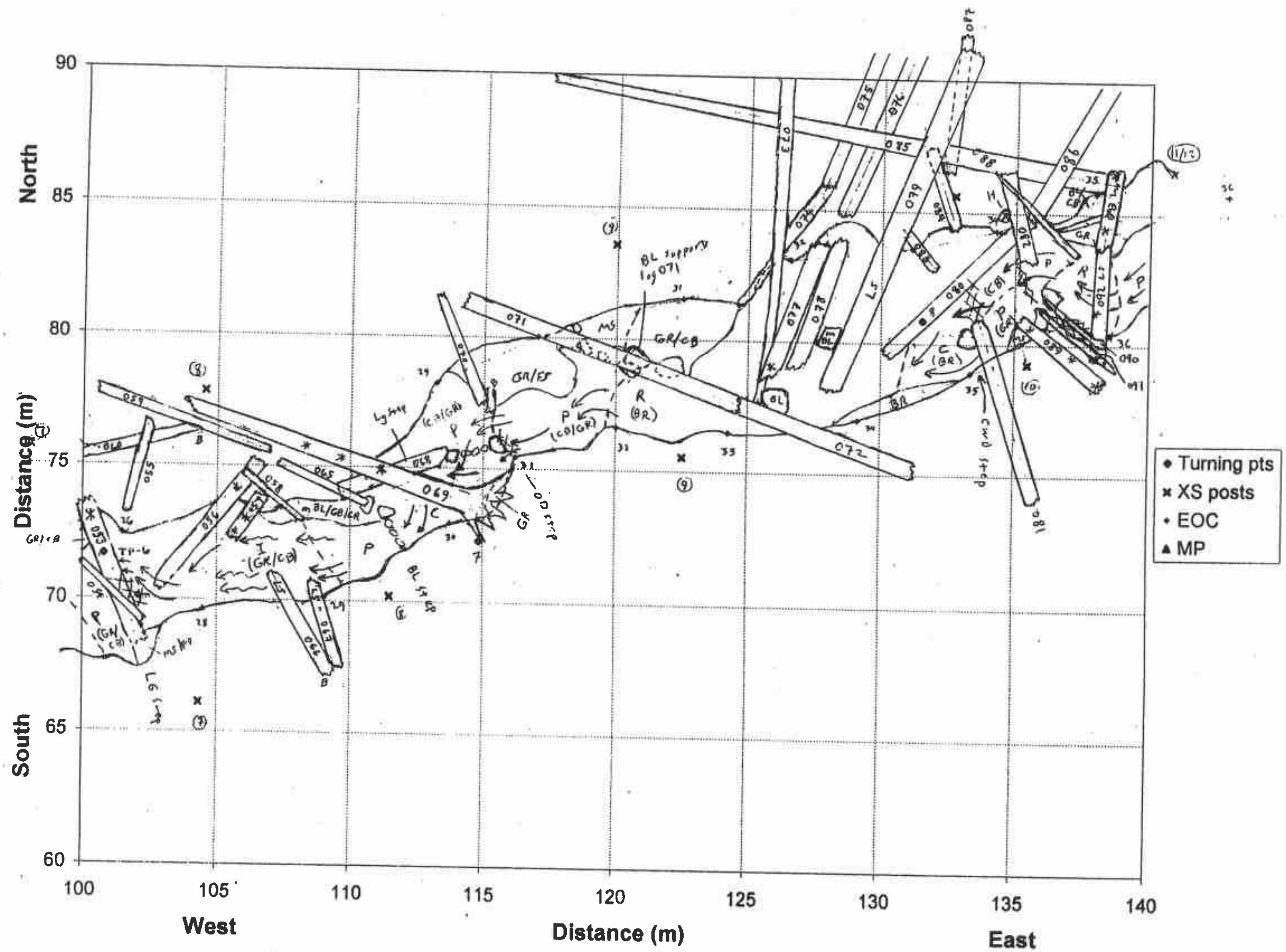

Figure C.4. Map of Cold Creek (COC) site, summer 1998, segment D.

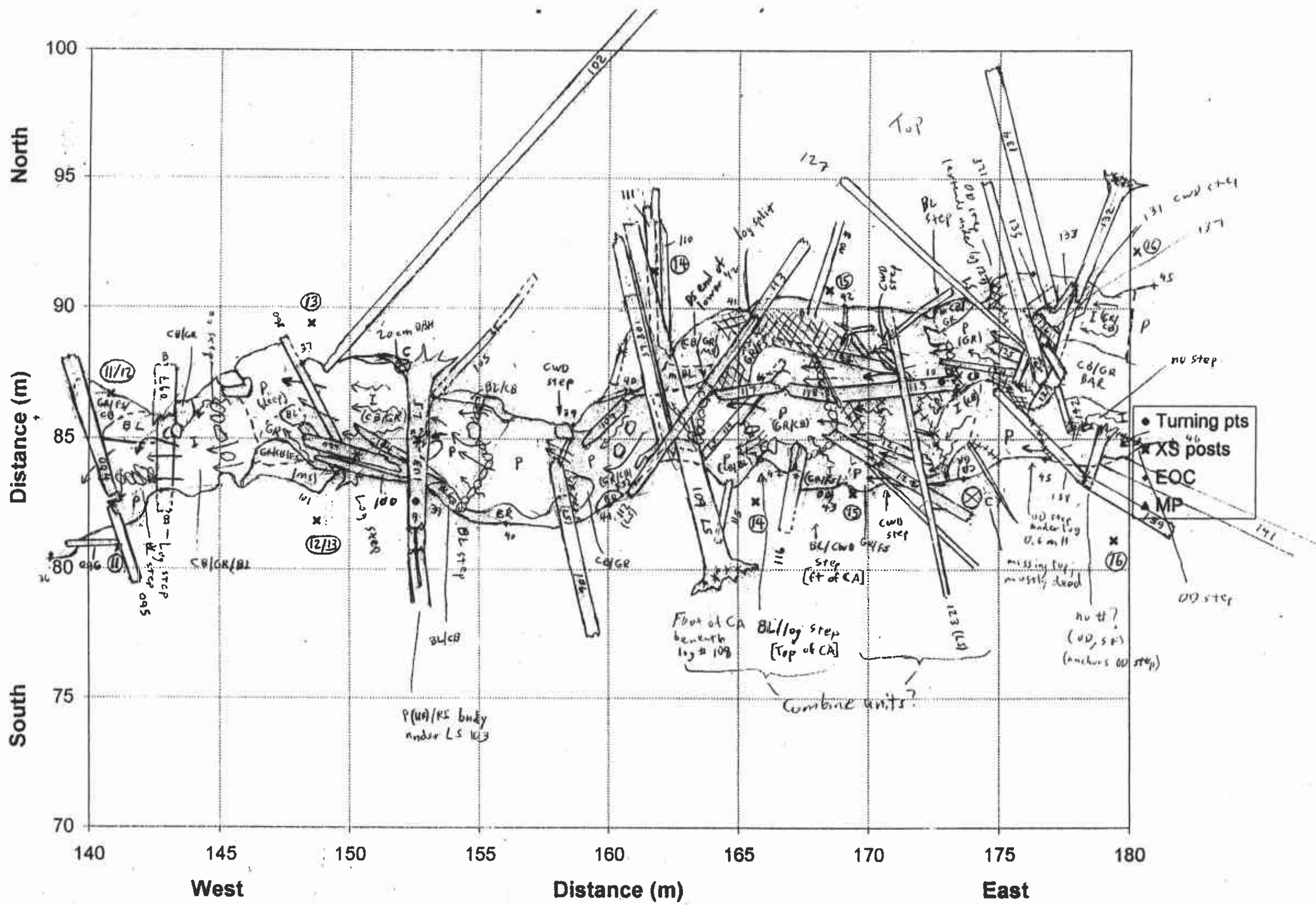

Figure C.5. Map of Cold Creek (COC) site, summer 1998, segment E.

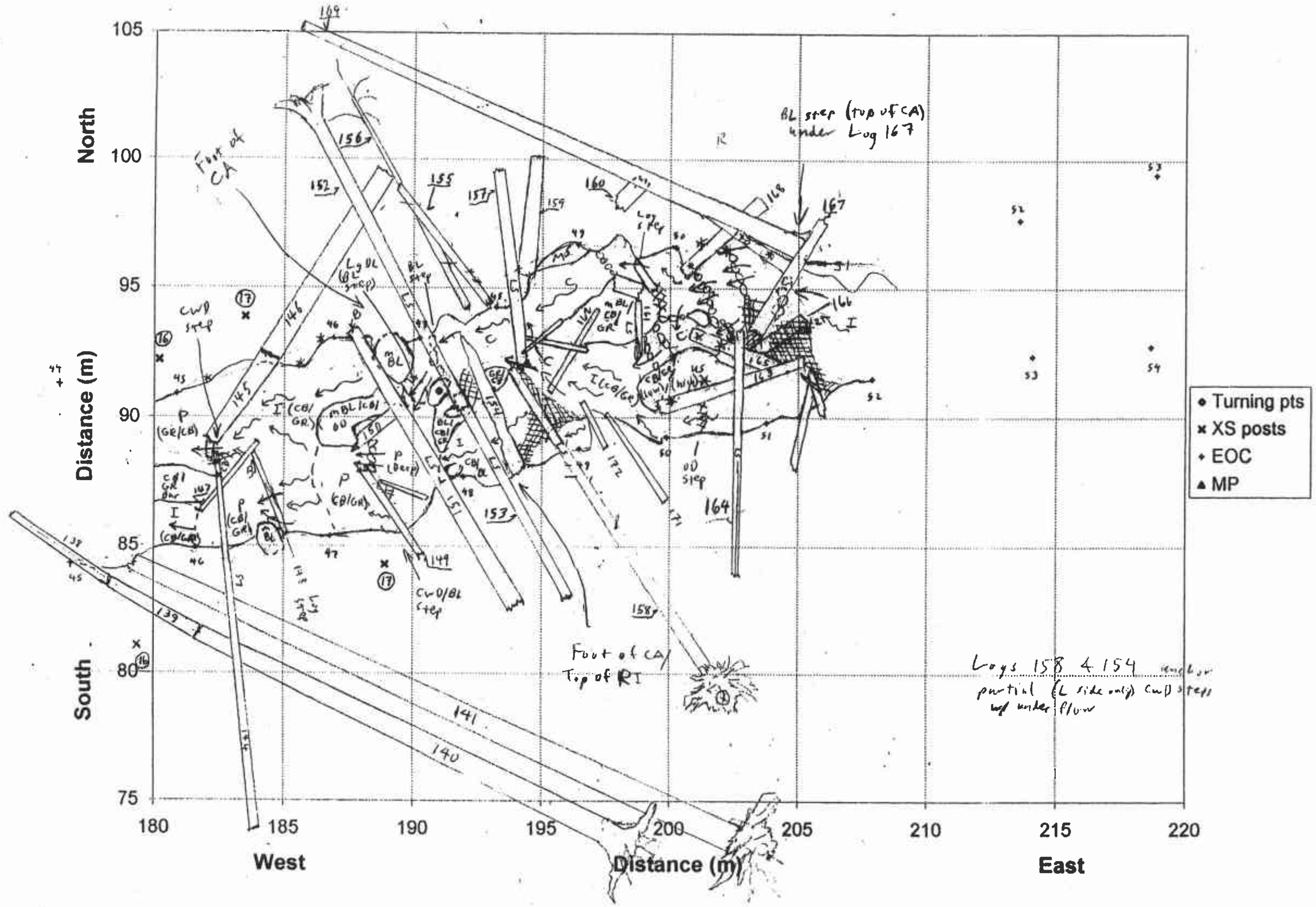

Figure C.6. Map of Cold Creek (COC) site, summer 1998, segment F.

Appendix D

Annual Maximum Peak Flow Data and Flood Frequency Analysis Results for Lookout Creek, Mack Creek, and Watershed 8

Table D.1. Annual maximum instantaneous peak discharge values for Lookout Creek.

Water Year	Date of peak	Q cfs	Q m^3/s	Q^{*} (1) $m^3/s/km^2$
1950	02/24/50	1980	56.1	0.898
1951	10/29/50	1800	51.0	0.817
1952	10/23/51	1320	37.4	0.599
1953	01/18/53	3620	102.5	1.642
1954	11/22/53	2490	70.5	1.130
1955	12/30/54	1150	32.6	0.522
1956	NA	NA	NA	NA
1957	NA	NA	NA	NA
1958	NA	2975	84.2	1.350
1959	NA	1246	35.3	0.565
1960	NA	943	26.7	0.428
1961	NA	2339	66.2	1.061
1962	NA	1923	54.4	0.872
1963	NA	1419	40.2	0.644
1964	11/08/63	1380	39.1	0.626
1965	12/22/64	6660	188.6	3.021
1966	01/06/66	1140	32.3	0.517
1967	01/28/67	1560	44.2	0.708
1968	02/23/68	1960	55.5	0.889
1969	12/04/68	2160	61.2	0.980
1970	01/18/70	1920	54.4	0.871
1971	01/18/71	2360	66.8	1.071
1972	01/21/72	4180	118.4	1.896
1973	12/20/72	822	23.3	0.373
1974	01/15/74	1310	37.1	0.594
1975	01/25/75	1320	37.4	0.599
1976	01/08/76	1630	46.2	0.739
1977	03/09/77	293	8.3	0.133
1978	11/25/77	3050	86.4	1.384
1979	12/04/78	1160	32.8	0.526
1980	01/12/80	1560	44.2	0.708
1981	12/25/80	2220	62.9	1.007
1982	12/06/81	1750	49.6	0.794
1983	12/04/82	1470	41.6	0.667
1984	02/13/84	2100	59.5	0.953

Table D.1. (continued)

Water Year	Date of peak	Q cfs	Q m^3/s	$Q^{*\ (1)}$ $m^3/s/km^2$
1985	11/02/84	1130	32.0	0.513
1986	02/23/86	2700	76.5	1.225
1987	11/28/86	970	27.5	0.440
1988	12/09/87	1090	30.9	0.494
1989	01/09/89	1680	47.6	0.762
1990	01/07/90	1960	55.5	0.889
1991	01/12/91	1010	28.6	0.458
1992	11/26/91	1110	31.4	0.504
1993	03/18/93	1220	34.5	0.553
1994	01/03/94	827	23.4	0.375
1995	01/13/95	1770	50.1	0.803
1996	02/07/96	8000	226.5	3.629
1997	11/19/96	2980	84.4	1.352
1998	10/30/97	1470	41.6	0.667

Source: Data sets were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station, Corvallis, Oregon.

(1) Unit area discharge based on drainage area of 6242 ha ($62.42\ km^2$).

Table D.2. Annual maximum instantaneous peak discharge values for Mack Creek.

Water Year	Date of peak	Q cfs	Q m^3/s	$Q^{*(1)}$ $m^3/s/km^2$
1980	01/13/80	202.4	5.73	0.986
1981	12/25/80	245.2	6.94	1.195
1982	02/20/82	221.9	6.28	1.081
1983	12/04/82	144.8	4.10	0.706
1984	02/13/84	188.5	5.34	0.919
1985	11/03/84	149.6	4.23	0.729
1986	02/23/86	287.2	8.13	1.400
1987	11/28/86	83.8	2.37	0.408
1988	12/09/87	136.2	3.86	0.664
1989	11/22/88	133.2	3.77	0.649
1990	01/07/90	228.2	6.46	1.112
1991	11/25/90	135.3	3.83	0.659
1992	11/25/91	136.9	3.88	0.667
1993	03/18/93	149.7	4.24	0.730
1994	01/03/94	100.5	2.85	0.490
1995	01/13/95	164.6	4.66	0.802
1996	02/07/96	330.2	9.35	1.609
1997	11/19/96	245.2	6.94	1.195
1998	01/11/98	180.3	5.11	0.879

Source: Data sets were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station. Corvallis. Oregon.

(1) Unit area discharge based on drainage area of 581 ha ($5.81\ km^2$).

Table D.3. Annual maximum instantaneous peak discharge values for watershed 8 (WS 8).

Water Year	Date of peak	Q cfs	Q m^3/s	$Q^{*\,(1)}$ $m^3/s/km^2$
1964	11/08/63	2.64	0.1	0.349
1965	12/22/64	14.33	0.4	1.896
1966	01/06/66	2.39	0.1	0.316
1967	01/28/67	3.66	0.1	0.484
1968	02/23/68	4.44	0.1	0.588
1969	12/04/68	5.36	0.2	0.709
1970	01/18/70	4.20	0.1	0.556
1971	01/18/71	5.77	0.2	0.763
1972	01/21/72	10.77	0.3	1.425
1973	01/13/73	2.90	0.1	0.383
1974	01/15/74	6.48	0.2	0.857
1975	12/20/74	4.46	0.1	0.590
1976	12/04/75	8.02	0.2	1.061
1977	04/08/77	1.47	0.0	0.194
1978	12/13/77	11.10	0.3	1.469
1979	02/10/79	3.71	0.1	0.491
1980	01/13/80	4.75	0.13	0.628
1981	12/25/80	7.94	0.22	1.050
1982	12/06/81	6.00	0.17	0.794
1983	12/04/82	5.62	0.16	0.743
1984	02/13/84	5.94	0.17	0.785
1985	11/02/84	3.24	0.09	0.428
1986	02/23/86	8.31	0.24	1.100
1987	11/27/86	3.17	0.09	0.420
1988	12/09/87	3.89	0.11	0.515
1989	11/22/88	3.66	0.10	0.485
1990	01/07/90	6.17	0.17	0.817
1991	01/12/91	3.36	0.10	0.444
1992	11/26/91	2.67	0.08	0.354
1993	03/17/93	4.00	0.11	0.529
1994	03/03/94	1.66	0.05	0.220
1995	01/13/95	5.19	0.15	0.687

Table D.3. (continued)

Water Year	**Date of peak**	***Q*** **cfs**	***Q*** **m^3/s**	***Q**** [(1)] **$m^3/s/km^2$**
1996	02/07/96	13.95	0.39	1.845
1997	11/19/96	9.40	0.27	1.244

Source: Data sets were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station, Corvallis, Oregon.

[(1)] Unit area discharge based on drainage area of 21.4 ha ($0.214 km^2$).

Table D.4. Ranked annual maximum peak flows (Q), unit area peak flows (Q^*), and associated Weibull plotting position values (p_x) and estimated recurrence interval (RI) for Lookout Creek, Mack Creek, and Watershed 8.

Lookout Creek						Mack Creek						Watershed 8					
Rank	Water Year	Q m³/s	Q^* m³/s/km²	p_x	RI yr	Rank	Water Year	Q m³/s	Q^* m³/s/km²	p_x	RI yr	Rank	Water Year	Q m³/s	Q^* m³/s/km²	p_x	RI yr
1	1996	226.5	3.629	0.021	48	1	1996	9.35	1.609	0.05	20	1	1965	0.406	1.896	0.029	35
2	1965	188.6	3.021	0.042	24	2	1986	8.13	1.400	0.10	10	2	1996	0.395	1.845	0.057	18
3	1972	118.4	1.896	0.063	16	3	1997	6.94	1.195	0.15	6.7	3	1978	0.314	1.469	0.086	12
4	1953	102.5	1.642	0.083	12	4	1981	6.94	1.195	0.20	5.0	4	1972	0.305	1.425	0.114	8.8
5	1978	86.4	1.384	0.104	9.6	5	1990	6.46	1.112	0.25	4.0	5	1997	0.266	1.244	0.143	7.0
6	1997	84.4	1.352	0.125	8.0	6	1982	6.28	1.081	0.30	3.3	6	1986	0.235	1.100	0.171	5.8
7	1958	84.2	1.350	0.146	6.9	7	1980	5.73	0.986	0.35	2.9	7	1976	0.227	1.061	0.200	5.0
8	1986	76.5	1.225	0.167	6.0	8	1984	5.34	0.919	0.40	2.5	8	1981	0.225	1.050	0.229	4.4
9	1954	70.5	1.130	0.188	5.3	9	1998	5.11	0.879	0.45	2.2	9	1974	0.183	0.857	0.257	3.9
10	1971	66.8	1.071	0.208	4.8	10	1995	4.66	0.802	0.50	2.0	10	1990	0.175	0.817	0.286	3.5
11	1961	66.2	1.061	0.229	4.4	11	1993	4.24	0.730	0.55	1.82	11	1982	0.170	0.794	0.314	3.2
12	1981	62.9	1.007	0.250	4.0	12	1985	4.23	0.729	0.60	1.67	12	1984	0.168	0.785	0.343	2.9
13	1969	61.2	0.980	0.271	3.7	13	1983	4.10	0.706	0.65	1.54	13	1971	0.163	0.763	0.371	2.7
14	1984	59.5	0.953	0.292	3.4	14	1992	3.88	0.667	0.70	1.43	14	1983	0.159	0.743	0.400	2.5
15	1950	56.1	0.898	0.313	3.2	15	1988	3.86	0.664	0.75	1.33	15	1969	0.152	0.709	0.429	2.3
16	1968	55.5	0.889	0.333	3.0	16	1991	3.83	0.659	0.80	1.25	16	1995	0.147	0.687	0.457	2.2
17	1990	55.5	0.889	0.354	2.8	17	1989	3.77	0.649	0.85	1.18	17	1980	0.134	0.628	0.486	2.1
18	1962	54.4	0.872	0.375	2.7	18	1994	2.85	0.490	0.90	1.11	18	1975	0.126	0.590	0.514	1.94
19	1970	54.4	0.871	0.396	2.5	19	1987	2.37	0.408	0.95	1.05	19	1968	0.126	0.588	0.543	1.84
20	1951	51.0	0.817	0.417	2.4							20	1970	0.119	0.556	0.571	1.75
21	1995	50.1	0.803	0.438	2.3							21	1993	0.113	0.529	0.600	1.67
22	1982	49.6	0.794	0.458	2.2							22	1988	0.110	0.515	0.629	1.59
23	1989	47.6	0.762	0.479	2.1							23	1979	0.105	0.491	0.657	1.52
24	1976	46.2	0.739	0.500	2.0							24	1989	0.104	0.485	0.686	1.46
25	1967	44.2	0.708	0.521	1.92							25	1967	0.104	0.484	0.714	1.40

Table D.4. (continued)

		Lookout Creek						Mack Creek						Watershed 8			
Rank	Water Year	Q m^3/s	Q^* m^3/s/km^2	p_x	RI yr	Rank	Water Year	Q m^3/s	Q^* m^3/s/km^2	p_x	RI yr	Rank	Water Year	Q m^3/s	Q^* m^3/s/km^2	p_x	RI yr
26	1980	44.2	0.708	0.542	1.85							26	1991	0.095	0.444	0.743	1.35
27	1983	41.6	0.667	0.563	1.78							27	1985	0.092	0.428	0.771	1.30
28	1998	41.6	0.667	0.583	1.71							28	1987	0.090	0.420	0.800	1.25
29	1963	40.2	0.644	0.604	1.66							29	1973	0.082	0.383	0.829	1.21
30	1964	39.1	0.626	0.625	1.60							30	1992	0.076	0.354	0.857	1.17
31	1952	37.4	0.599	0.646	1.55							31	1964	0.075	0.349	0.886	1.13
32	1975	37.4	0.599	0.667	1.50							32	1966	0.068	0.316	0.914	1.09
33	1974	37.1	0.594	0.688	1.45							33	1994	0.047	0.220	0.943	1.06
34	1959	35.3	0.565	0.708	1.41							34	1977	0.042	0.194	0.971	1.03
35	1993	34.5	0.553	0.729	1.37												
36	1979	32.8	0.526	0.750	1.33												
37	1955	32.6	0.522	0.771	1.30												
38	1966	32.3	0.517	0.792	1.26												
39	1985	32.0	0.513	0.813	1.23												
40	1992	31.4	0.504	0.833	1.20												
41	1988	30.9	0.494	0.854	1.17												
42	1991	28.6	0.458	0.875	1.14												
43	1987	27.5	0.440	0.896	1.12												
44	1960	26.7	0.428	0.917	1.09												
45	1994	23.4	0.375	0.938	1.07												
46	1973	23.3	0.373	0.958	1.04												
47	1977	8.3	0.133	0.979	1.02												

Table D.5. Summary statistics used in fitting Log Pearson Type III (LP3) frequency distribution to annual maximum peak unit area discharge (Q^*) series for Lookout Creek, Mack Creek, and Watershed 8.

	Lookout Creek			Mack	WS 8
Parameter	original data	1977 omitted	synthetic statistics [(3)]	original data	original data
Years of record, N	47	46	46	19	34
Mean of X, X_{avg} [(1)]	-0.116	-0.100	-0.105	-0.076	-0.194
Standard deviation of X, S	0.240	0.214	0.216	0.153	0.239
Station skew, G [Eq. 4a] [(2)]	0.174	1.050	0.628	-0.069	0.040
High outlier threshold, X_H [Eq. 7]	0.543	0.486		0.284	0.433
Max. log unit area discharge, X_{max}	0.560	0.560		0.207	0.278
Low outlier threshold, X_H [Eq. 8a]	-0.775	-0.685		-0.437	-0.820
Min. log unit area discharge, X_{min}	-0.876	-0.428		-0.389	-0.711
Mean square error of station skew, MSE_G [Eq. 6]	0.121	0.205	0.160	0.262	0.151
Generalized skew (from Plate I of Bull. 17B)	0.02	0.04	0.04	0.04	0.04
MSE of generalized skew (from Bull. 17B)	0.302	0.302	0.302	0.302	0.302
Weighted skew, G_w [Eq. 5]	0.130	0.641	0.424	-0.018	0.040

Notes:

(1) $X = \log_{10} Q^*$ (i.e., the base 10 logarithm of the annual maximum peak unit area discharge in $m^3/s/km^2$)

(2) Equation numbers in square brackets refer to equations in Bulletin 17B.

(3) Synthetic statistics for frequency curve adjusted for removal of low outlier. Synthetic mean, standard deviation, and skew computed using Bulletin 17B equations 5-5, 5-4, and 5-3, respectively.

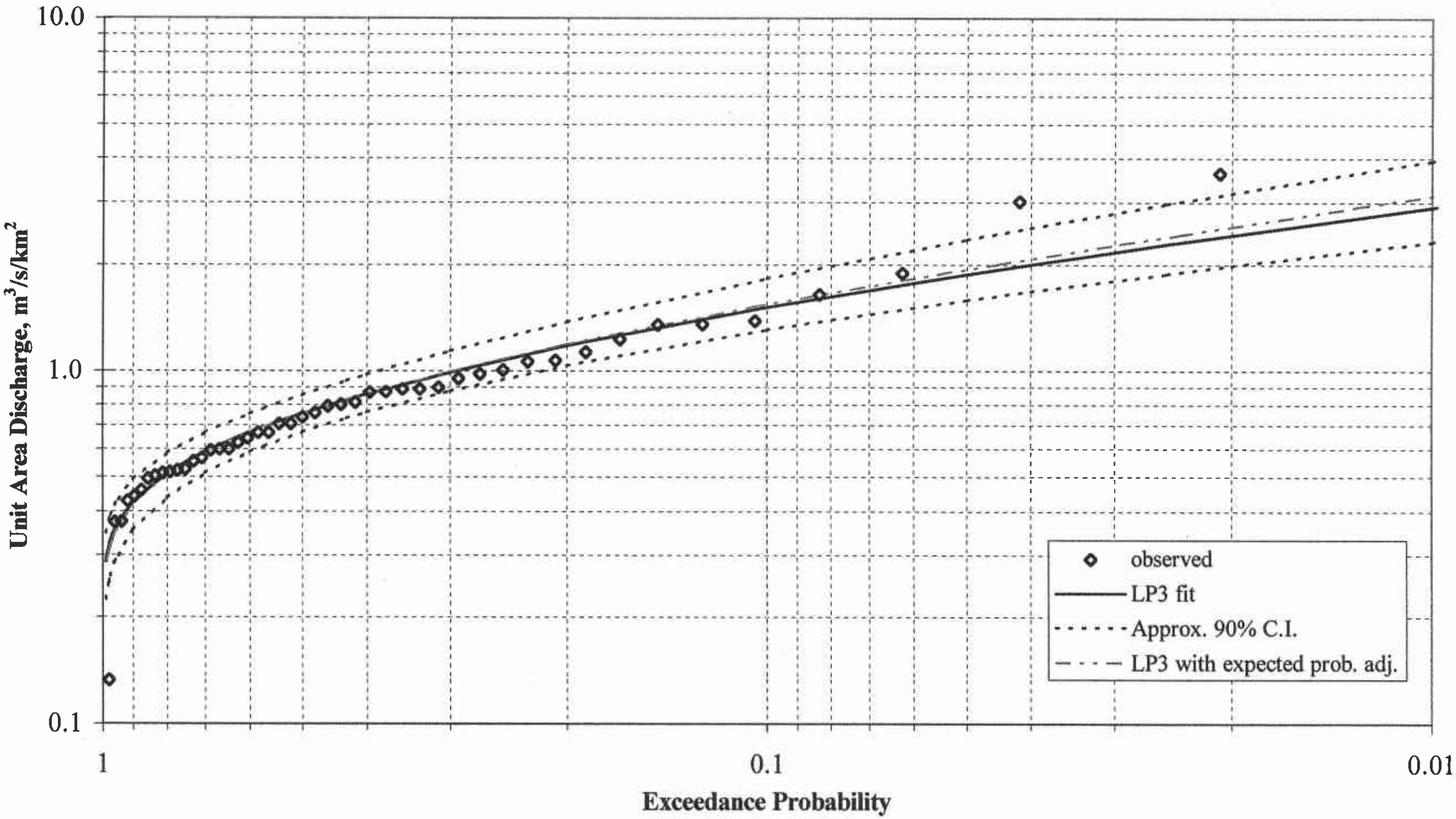

Figure D.1. Frequency plot for Lookout Creek annual maximum instantaneous peak flows, showing fitted Log Pearson Type III frequency plot with and without expected probability adjustment and an approximate 90% confidence interval.

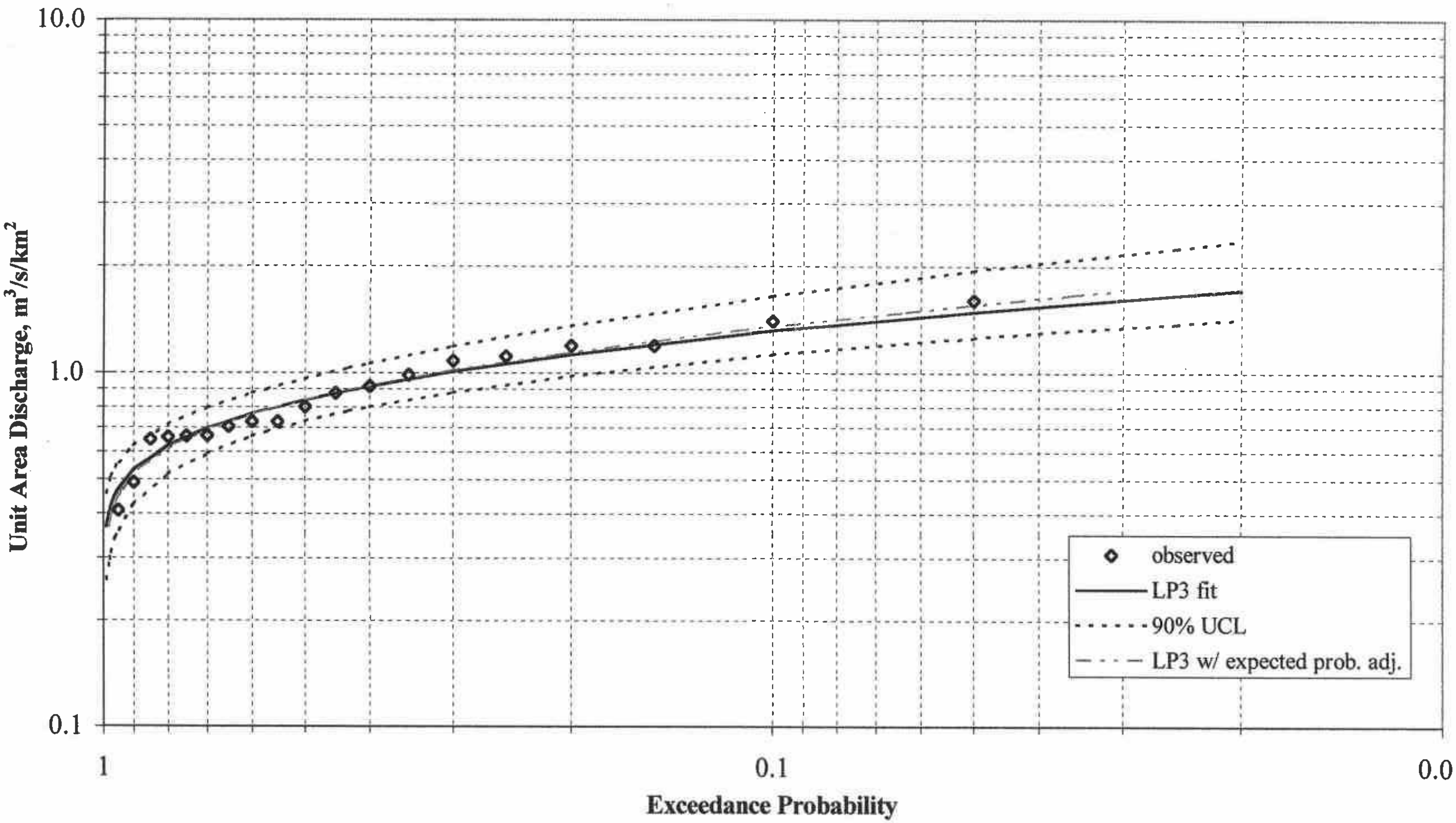

Figure D.2. Frequency plot for Mack Creek annual maximum instantaneous peak flows, showing fitted Log Pearson Type III frequency plot with and without expected probability adjustment and an approximate 90% confidence interval.

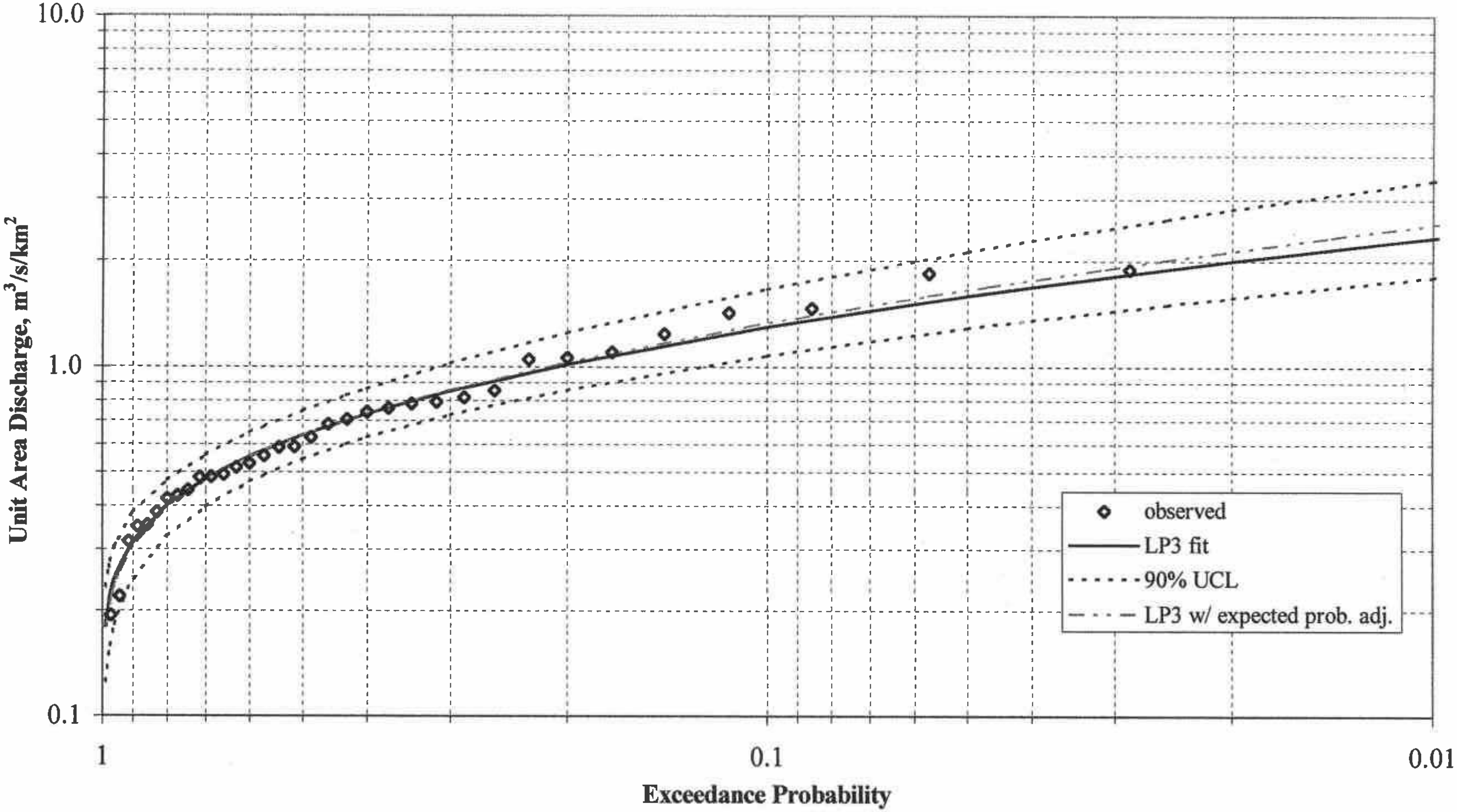

Figure D.3. Frequency plot for WS 8 annual maximum instantaneous peak flows, showing fitted Log Pearson Type III frequency plot with and without expected probability adjustment and an approximate 90% confidence interval.

Appendix E

Classified Cross Section Change Scores

Table E.1. Classified cross section change scores for lower Lookout Creek (LOL) site, 1978-1998.

XS No.	1978	1980	1981	1982	1984	1985	1986	1988	1989	1990	1995	1996	1997	1998	No. = '3'	No. ≥ '2'	No. ≥ '1'	*n*
1	OK	1	0	2	2	1	0	0	0	0	0	3	2	0	1	4	6	13
2	OK	0	0	0	0	0	2	0	0	0	1	3	2	0	1	3	4	13
3	OK	1	2	0	0		X	0	0	0	0	3	2	0	1	3	4	11
4	OK	1	1	0	1	0	1	0	0	0	1	3	1	0	1	1	7	13
5	OK	0	0	2	0	0	1	0	0	0	0	3	1	0	1	2	4	13
6	OK	X	2	3	2	2	3	2	0	2	2	3	2	0	3	10	10	12
7	OK	X	2	2	0	0	2	0	0	0	0	3	0	0	1	4	4	12
8	OK	2	1	2	2	0	3	0	0	1	0	3	1	0	2	5	8	13
9	OK	0	0	0	2	0	2	0	0	0	0	3	1	0	1	3	4	13
10 (1)	*X*	*OK*	*1**	*0**	*1**	*1**	*2**	*1**	*0**	*0**	*1**	*3**	*0**	*0**	*1*	*2*	*7*	*12*
11	OK	2	1	1	1	0	2	0	0	1	1	3	2	2	1	5	10	13
12	OK	0	0	0	0	0	1	0	0	0	0	3	2	1	1	2	4	13
13	OK	1	1	0	0		2	0	1	0	1	3	3	0	2	3	7	12
14	OK	0	2	1	1		2	0	1	0	0	2	2	0	0	4	7	12
No. = '3'		0	0	1	0	0	2	0	0	0	0	12	1	0				
No. = '2'		2	4	4	4	1	6	1	0	1	1	1	7	1				
No. = '1'		4	4	2	3	1	3	0	2	2	4	0	4	1				
No. ≥ '2'		2	4	5	4	1	8	1	0	1	1	13	8	1				
No. ≥ '1'		6	8	7	7	2	11	1	2	3	5	13	12	2				
Count, *m*		11	13	13	13	10	12	13	13	13	13	13	13	13				
Proportion = '3'		0.00	0.00	0.08	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.92	0.08	0.00				
Proportion ≥ '2'		0.18	0.31	0.38	0.31	0.10	0.67	0.08	0.00	0.08	0.08	1.00	0.62	0.08				
Proportion ≥ '1'		0.55	0.62	0.54	0.54	0.20	0.92	0.08	0.15	0.23	0.38	1.00	0.92	0.15				
Response Index (2)		0.24	0.31	0.33	0.28	0.10	0.58	0.05	0.05	0.10	0.15	0.97	0.54	0.08				

See explanation and notes following Table E.4.

Table E.2. Classified cross section change scores for middle Lookout Creek (LOM) site, 1978-1998.

XS No.	1978	1980	1981	1982	1984	1985	1986	1988	1989	1990	1995	1996	1997	1998	No. = '3'	No. ≥ '2'	No. ≥ '1'	*n*
1	OK	0	0	0	1	0	2	0	0	1	0	3	1	0	1	2	5	13
2	OK	1	0	0	1	0	2	0	0	0	0	3	2	0	1	3	5	13
3	OK	0	0	1	0	0	1	0	0	0	0	3	1	0	1	1	4	13
4	OK	0	0	0	0	0	1	0	0	0	0	3	0	0	1	1	2	13
5	OK	1	1	0	1	0	2	0	0	1	1	3	2	0	1	3	8	13
6	OK	0	0	0	0	0	1	0	1	1	1	3	1	1	1	1	7	13
7	X		OK	0	0	0	3	0	0	1	0	3	2	0	2	3	4	11
8/9.5 [(1)]	*OK*		*1**	*0**			*OK*	*0**	*0**	*1**	*0**	*OK*	*2**	*0**	*0*	*1*	*3*	*8*
9 [(1)]	*OK*		*2**	*0**	*1**	*2**	*3**	*0**	*0**	*2**	*0**	*3**	*1**	*1**	*2*	*5*	*8*	*12*
10	OK		1	0	0	0	3	0	1	1	0	3	2	0	2	3	6	12
11	OK		1	1	0	0	3	1	0	0	1	3	1	0	2	2	7	12
No. = '3'		0	0	0	0	0	3	0	0	0	0	9	0	0				
No. = '2'		0	0	0	0	0	3	0	0	0	0	0	4	0				
No. = '1'		2	3	2	3	0	3	1	2	5	3	0	4	1				
No. ≥ '2'		0	0	0	0	0	6	0	0	0	0	9	4	0				
No. ≥ '1'		2	3	2	3	0	9	1	2	5	3	9	8	1				
Count, *m*		6	8	9	9	9	9	9	9	9	9	9	9	9				
Proportion = '3'		0.00	0.00	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	1.00	0.00	0.00				
Proportion ≥ '2'		0.00	0.00	0.00	0.00	0.00	0.67	0.00	0.00	0.00	0.00	1.00	0.44	0.00				
Proportion ≥ '1'		0.33	0.38	0.22	0.33	0.00	1.00	0.11	0.22	0.56	0.33	1.00	0.89	0.11				
Response Index [(2)]		0.11	0.13	0.07	0.11	0.00	0.67	0.04	0.07	0.19	0.11	1.00	0.44	0.04				

See explanation and notes following Table E.4.

Table E.3. Classified cross section change scores for Mack Creek clearcut (MCC) site, 1981-1997.

XS No.	1981	1982	1983	1984	1985	1986	1988	1990	1995	1996	1997	No. = '3'	No. ≥ '2'	No. ≥ '1'	*n*
101 [(1)]	*OK*	*0**	*0**	*0**	*0**	*2**	*1**	*0**	*1**	*3**	*1**	*1*	*2*	*5*	*10*
102 [(1)]	*OK*	*0**	*0**	*0**	*0**	*1**	*0**	*0**	*0**	*3**	*0**	*1*	*1*	*2*	*10*
103	OK	0	0	1	0	1	0	0	0	2	2	0	2	4	10
104	OK	0	1	1	1	1	0	1	2	2	0	0	2	7	10
105	OK	0	0	0	0	2	0	0	0	3	0	1	2	2	10
106	OK	0	0	0	0	0	0	0	1	2	1	0	1	3	10
107	OK	3	0	0	0	1	0	1	0	2	1	1	2	5	10
108	OK	2	2	1	0	1	1	2	2	3	2	1	6	9	10
109	OK	0	0	0	0	0	0	2	2	3	0	1	3	3	10
110	OK	2		0	0	2	1	2	2	3	2	1	6	7	9
111	OK	0		0	X	0	0	1	1	2	0	0	1	3	8
112	X	OK		2	X	0	0	0	1	3	0	1	2	3	7
113	OK	1		0	1	2	0	0	1	2	0	0	2	5	9
114	OK	2		1	0	1	0	1	1	3	0	1	2	6	9
115	OK	2		1	0	1	0	0		3	1	1	2	5	8
117	OK	0		OK[(3)]	1	1	1	0	0	OK	1	0	0	4	7
118	OK	0		0	0	2	1	1	1	3	2	1	3	6	9
119	OK	0		1	0	1	0	1	0	1	0	0	0	4	9
120	OK	1		0	0	2	0	1	1	2	0	0	2	5	9
No. = '3'		1	0	0	0	0	0	0	0	8	0				
No. = '2'		4	1	1	0	5	0	3	4	7	4				
No. = '1'		2	1	6	3	8	4	7	7	1	4				
No. ≥ '2'		5	1	1	0	5	0	3	4	15	4				
No. ≥ '1'		7	2	7	3	13	4	10	11	16	8				
Count, *m*		16	7	16	15	17	17	17	16	16	17				
Proportion = '3'		0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00				
Proportion ≥ '2'		0.31	0.14	0.06	0.00	0.29	0.00	0.18	0.25	0.94	0.24				
Proportion ≥ '1'		0.44	0.29	0.44	0.20	0.76	0.24	0.59	0.69	1.00	0.47				
Response Index[(2)]		0.27	0.14	0.17	0.07	0.35	0.08	0.25	0.31	0.81	0.24				

See explanation and notes following Table E.4.

Table E.4. Classified cross section change scores for Mack Creek old-growth (MAC) site, 1978-1997.

XS No.	1978	1980	1981	1982	1983	1984	1985	1986	1988	1990	1995	1996	1997	No. = '3'	No. ≥ '2'	No. ≥ '1'	*n*
1[1]	*OK*	*1**	*0**	*0**	*0**	*1**	*2**	*1**	*0**	*0**	*1**	*3**	*0**	*1*	*2*	*6*	*12*
2[1]	*OK*	*1**	*2**	*2**	*0**	*2**	*0**	*2**	*0**	*0**	*1**	*2**	*0**	*0*	*5*	*7*	*12*
3	OK	1	1	1	0	1	0	2	0	0	2	3	0	1	3	7	12
4	OK	1	1	0	0	1	1	1	0	0	0	2	1	0	1	7	12
5	OK	0	0	0	0	0	0	0	0	0	1	1	1	0	0	3	12
7	OK	0	0	0	0	3	0	2	0	1	0	3	0	2	3	4	12
8	OK	1	0	0	0	0	0	1	0	1	0	1	0	0	0	4	12
9	OK	1	0	0	0	0	0	2	0	0	0	2	1	0	2	4	12
10	OK	0	0	0	0	0	0	0	0	0	0	3	1	1	1	2	12
11	OK	0	0	0	0	1	0	2	0	0	0	3	1	1	2	4	12
12	OK	0	0	0	0	0	0	1	0	2	0	2	1	0	2	4	12
No. = '3'		0	0	0	0	1	0	0	0	0	0	4	0				
No. = '2'		0	0	0	0	0	0	4	0	1	1	3	0				
No. = '1'		4	2	1	0	3	1	3	0	2	1	2	6				
No. ≥ '2'		0	0	0	0	1	0	4	0	1	1	7	0				
No. ≥ '1'		4	2	1	0	4	1	7	0	3	2	9	6				
Count, *m*		9	9	9	9	9	9	9	9	9	9	9	9				
Proportion = '3'		0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.44	0.00				
Proportion ≥ '2'		0.00	0.00	0.00	0.00	0.11	0.00	0.44	0.00	0.11	0.11	0.78	0.00				
Proportion ≥ '1'		0.44	0.22	0.11	0.00	0.44	0.11	0.78	0.00	0.33	0.22	1.00	0.67				
Response Index[2]		0.15	0.07	0.04	0.00	0.22	0.04	0.41	0.00	0.15	0.11	0.74	0.22				

See explanation and notes following Table E.4.

Explanation and notes for Tables E.1 through E.4.

Explanation

0	No significant detectable change
1	Minor but clearly detectable change
2	Moderate change
3	Substantial change
X	Data not usable
OK	First year of data for profile after establishment or reestablishment
	Blank entries indicate profile not surveyed that year

Notes

(1) Italicized rows (values marked by asterisks) were excluded from logistic regression analysis and are not reflected in summary statistics in bottom 10 rows of Tables E.1 through E.4. Reasons for exclusion are listed below.

(2) Response index is calculated as the sum of the individual XS change scores for a given year divided by the total possible sum of scores $(3 \times m)$.

(3) Tape attached to wrong posts in 1984 & 85; not comparable with other years. The 1986 value is change at original profile location vs. 1982.

Cross sections excluded from analysis and reasons for exclusion:

Site	XS No.	Reason for exclusion
LOL	10	Lack of independence--close to XS 9 (same channel unit) & shares post with XS 11.
LOM	8/9.5	Unreliable due to location changes and abundant LWD. Three different locations at different times (1978-82, 196-95, 1996-98).
	9	Unreliable due to location changes and abundant LWD. Actually a combination of LOM 9 (1978-85, 1996-98) and LOM 8 (1986-95) as recorded on data sheets, but all believed to be at approximately same location as at present.
MCC	101	Influenced by gaging station flume overfall.
	102	Influenced by gaging station flume overfall.
	116	Strongly diagonal to channel; shares post with XS 117.
MAC	1	Not representative of undisturbed old-growth forest; influenced by LWD removal, road crossing.
	2	Not representative of undisturbed old-growth forest; influenced by LWD removal, road crossing.
	6	Diagonal to channel & crosses LWD jam; channel bed obscured by LWD.

Appendix F

Estimated Average Depths of Scour and Fill at Cross Sections Locations, 1995-96 and 1985-86

Table F.1. Average depth of scour and fill (in meters) at cross section locations, 1995-96.

Site	XS No.	Scour	Fill	Net Δ [1]	Total Δ [2]	Tot. Δ/D_{50} [3]
COC	01	0.00	0.16	+0.16	0.16	1.67
COC	02	0.12	0.04	- 0.08	0.16	1.67
COC	03	0.12	0.10	- 0.02	0.22	2.39
COC	04	0.02	0.02	0.00	0.03	0.37
COC	05	0.02	0.13	+0.11	0.14	1.52
COC	06	0.05	0.08	+0.03	0.12	1.31
COC	08	0.17	0.01	- 0.15	0.18	1.91
COC	09	0.02	0.02	0.00	0.04	0.40
COC	10	0.10	0.00	- 0.10	0.10	1.06
COC	13	0.22	0.03	- 0.18	0.25	2.66
COC	14	0.18	0.00	- 0.18	0.18	1.88
COC	15	0.12	0.01	- 0.10	0.13	1.36
COC	16	0.03	0.21	+0.18	0.24	2.58
COC	17	0.07	0.05	- 0.01	0.12	1.29
MAC	01	0.19	0.07	- 0.12	0.25	3.30
MAC	02	0.12	0.05	- 0.07	0.16	2.14
MAC	03	0.02	0.31	+0.30	0.33	4.33
MAC	04	0.07	0.02	- 0.05	0.09	1.19
MAC	05	0.10	0.01	- 0.09	0.11	1.45
MAC	07	0.08	0.27	+0.20	0.35	4.49
MAC	08	0.08	0.02	- 0.06	0.10	1.32
MAC	09	0.13	0.00	- 0.13	0.13	1.64
MAC	10	0.03	0.30	+0.27	0.34	4.36
MAC	11	0.29	0.04	- 0.26	0.33	4.25
MAC	12	0.05	0.01	- 0.04	0.07	0.86
MCC	120	0.11	0.04	- 0.06	0.14	2.54
MCC	119	0.03	0.07	+0.05	0.10	1.80
MCC	118	0.10	0.15	+0.06	0.25	4.34
MCC	115	0.34	0.02	- 0.31	0.36	6.31
MCC	114	0.23	0.02	- 0.21	0.25	4.44
MCC	113	0.08	0.02	- 0.06	0.10	1.83
MCC	112	0.20	0.00	- 0.20	0.20	3.44
MCC	111	0.22	0.02	- 0.20	0.24	4.17
MCC	110	0.05	0.21	+0.16	0.26	4.62
MCC	109	0.15	0.05	- 0.09	0.20	3.51
MCC	108	0.22	0.04	- 0.18	0.26	4.50
MCC	107	0.19	0.03	- 0.16	0.22	3.83

Table F.1. (continued)

Site	XS No.	Scour	Fill	Net Δ [1]	Total Δ [2]	Tot. Δ/D_{50} [3]
MCC	106	0.05	0.10	+0.05	0.15	2.56
MCC	105	0.06	0.16	+0.10	0.22	3.90
MCC	104	0.08	0.08	0.00	0.16	2.88
MCC	103	0.07	0.14	+0.07	0.20	3.59
MCC	102	0.51	0.02	- 0.48	0.53	9.31
MCC	101	0.29	0.03	- 0.26	0.31	5.50
LOM	11	0.34	0.43	+0.08	0.77	6.81
LOM	10	0.44	0.07	- 0.37	0.51	4.48
LOM	08	0.00	1.17	+1.17	1.17	10.38
LOM	07	0.04	0.53	+0.49	0.57	5.03
LOM	06	0.03	0.86	+0.83	0.90	7.95
LOM	05	0.02	0.76	+0.74	0.79	6.96
LOM	04	0.07	0.47	+0.40	0.54	4.75
LOM	03	0.00	0.37	+0.37	0.37	3.30
LOM	02	0.15	0.24	+0.09	0.39	3.49
LOM	01	0.21	0.10	- 0.11	0.30	2.67
LOL	01	0.00	0.59	+0.59	0.59	5.85
LOL	02	0.12	0.09	- 0.02	0.22	2.16
LOL	03	0.26	0.61	+0.35	0.87	8.72
LOL	04	0.22	0.35	+0.13	0.57	5.73
LOL	05	0.28	0.04	- 0.24	0.32	3.22
LOL	06	0.54	0.32	- 0.22	0.86	8.62
LOL	07	0.49	0.21	- 0.28	0.69	6.92
LOL	08	0.64	0.02	- 0.62	0.66	6.56
LOL	09	0.13	0.14	+0.01	0.27	2.68
LOL	11	0.57	0.09	- 0.48	0.65	6.51
LOL	12	0.15	0.10	- 0.04	0.25	2.50
LOL	13	0.05	0.22	+0.17	0.27	2.68
LOL	14	0.12	0.08	- 0.03	0.20	2.00

[1] Net Δ = Fill - Scour

[2] Total Δ = Fill + Scour

[3] D_{50} is the averager median particle diameter for all cross sections at a site.

Table F.2. Average depth of scour and fill (in meters) at cross section locations, 1985-86.

Site	XS No.	Scour	Fill	Net Δ [1]	Total Δ [2]	Tot. Δ/D_{50} [3]
COC	01	0.05	0.01	- 0.05	0.06	0.64
COC	02	0.06	0.00	- 0.06	0.06	0.68
COC	03	0.03	0.15	+0.15	0.18	1.91
COC	04	0.02	0.02	+0.02	0.04	0.41
COC	05	0.03	0.03	+0.00	0.05	0.58
COC	06	0.00	0.00	+0.00	0.00	0.00
COC	08	0.10	0.00	- 0.10	0.10	1.02
COC	09	0.04	0.06	+0.02	0.09	1.00
COC	10	0.06	0.02	- 0.04	0.09	0.91
COC	13	0.04	0.00	- 0.04	0.04	0.43
COC	14	0.02	0.00	- 0.02	0.02	0.18
COC	15	0.04	0.02	- 0.02	0.05	0.57
COC	16	0.00	0.10	+0.10	0.10	1.10
COC	17	0.00	0.05	+0.04	0.05	0.57
MAC	01	0.09	0.02	- 0.09	0.11	1.46
MAC	02	0.07	0.04	- 0.03	0.11	1.48
MAC	03	0.09	0.06	- 0.03	0.15	1.97
MAC	04	0.05	0.03	- 0.02	0.09	1.11
MAC	05	0.04	0.01	- 0.04	0.05	0.71
MAC	07	0.15	0.00	- 0.15	0.15	1.91
MAC	08	0.01	0.08	+0.06	0.09	1.17
MAC	09	0.05	0.04	- 0.01	0.10	1.24
MAC	10	0.05	0.04	- 0.01	0.09	1.16
MAC	11	0.02	0.16	+0.14	0.18	2.35
MAC	12	0.07	0.01	- 0.06	0.07	0.95
MCC	120	0.04	0.11	+0.08	0.15	2.69
MCC	119	0.06	0.04	- 0.02	0.10	1.82
MCC	118	0.02	0.15	+0.13	0.17	2.90
MCC	117	0.06	0.01	- 0.05	0.07	1.24
MCC	115	0.07	0.03	- 0.04	0.10	1.72
MCC	114	0.01	0.06	+0.05	0.07	1.21
MCC	113	0.01	0.11	+0.09	0.12	2.13
MCC	112	0.00	0.13	+0.13	0.13	2.34
MCC	111	0.04	0.11	+0.07	0.15	2.63
MCC	110	0.03	0.06	+0.03	0.10	1.68
MCC	109	0.06	0.01	- 0.06	0.07	1.26
MCC	108	0.08	0.04	- 0.05	0.12	2.15

Table F.2. (continued)

Site	XS No.	Scour	Fill	Net Δ [1]	Total Δ [2]	Tot. Δ/D_{50} [3]
MCC	107	0.04	0.09	+0.04	0.13	2.33
MCC	106	0.02	0.06	+0.04	0.07	1.24
MCC	105	0.09	0.03	- 0.05	0.13	2.27
MCC	104	0.02	0.05	+0.02	0.07	1.29
MCC	103	0.02	0.10	+0.09	0.12	2.07
MCC	102	0.08	0.00	- 0.08	0.08	1.49
MCC	101	0.07	0.05	- 0.01	0.11	1.99
LOM	11	0.07	0.17	+0.10	0.25	2.18
LOM	10	0.19	0.06	- 0.13	0.24	2.13
LOM	07	0.19	0.03	- 0.16	0.22	1.96
LOM	06	0.07	0.02	- 0.06	0.09	0.78
LOM	05	0.06	0.04	- 0.01	0.10	0.92
LOM	04	0.04	0.04	- 0.00	0.08	0.71
LOM	03	0.04	0.07	+0.03	0.11	0.95
LOM	02	0.03	0.08	+0.05	0.11	0.93
LOM	01	0.03	0.10	+0.07	0.13	1.17
LOL	01	0.04	0.03	- 0.01	0.07	0.66
LOL	02	0.06	0.02	- 0.04	0.08	0.80
LOL	04	0.05	0.05	+0.01	0.10	0.96
LOL	05	0.05	0.06	+0.01	0.10	1.03
LOL	06	0.16	0.37	+0.20	0.53	5.31
LOL	07	0.08	0.08	- 0.01	0.16	1.62
LOL	08	0.02	0.20	+0.18	0.22	2.16
LOL	09	0.00	0.15	+0.15	0.15	1.50
LOL	10	0.03	0.16	+0.13	0.18	1.82
LOL	11	0.06	0.11	+0.05	0.17	1.74
LOL	12	0.04	0.05	+0.01	0.09	0.89
LOL	13	0.00	0.12	+0.12	0.12	1.18
LOL	14	0.07	0.08	+0.01	0.15	1.50

(1) Net Δ = Fill - Scour

(2) Total Δ = Fill + Scour

(3) D_{50} is the averager median particle diameter for all cross sections at a site.

Appendix G

Logistic Regression Analysis Results

Table G.1(a). Summary of logistic regression analysis results using Q^* as explanatory variable [1].

Site	α	Std. Err.	t-stat	p-value	df	β	Std. Err.	t-stat	p-value	df
LOL	-4.58	0.839	-5.47	0.0002	11	5.07	0.973	5.21	0.0003	11
LOM	-5.86	1.126	-5.21	0.0003	11	6.13	1.270	4.83	0.0005	11
MCC	-3.96	0.807	-4.90	0.0017	7	3.75	0.752	4.98	0.0016	7
MAC	-6.15	1.206	-5.10	0.0005	10	5.22	1.100	4.75	0.0008	10

Table G.1(b). Summary of logistic regression analysis results using *log RI* as explanatory variable [1].

Site	α	Std. Err.	t-stat	p-value	df	β	Std. Err.	t-stat	p-value	df
LOL	-2.45	0.460	-5.33	0.0002	11	5.56	1.076	5.16	0.0003	11
LOM	-3.27	0.632	-5.18	0.0003	11	6.69	1.408	4.75	0.0006	11
MCC	-1.73	0.396	-4.38	0.0032	7	2.86	0.578	4.94	0.0017	7
MAC	-2.94	0.568	-5.17	0.0004	10	3.83	0.810	4.73	0.0008	10

[1] Logistic regression model fitted separately for each site; α and β are intercept and slope parameters, respectively.

Table G.2(a). Between-site contrasts in slope parameter in logistic regression analysis using Q^* and *Site* as explanatory variables[(1)].

Site 1	m_i	Site 2	m_i	Slope contrast[(2)]	Std. Error	t-stat	df	2-sided p-value
LOL	13	LOM	13	1.0627	1.5997	0.6643	22	0.5134
LOL	13	MCC	9	-1.3239	1.2297	-1.0766	18	0.2959
LOL	13	MAC	12	0.1509	1.4684	0.1028	21	0.9191
LOM	13	MCC	9	-2.3865	1.4758	-1.6171	18	0.1232
LOM	13	MAC	12	-0.9118	1.6799	-0.5427	21	0.5930
MCC	9	MAC	12	1.4748	1.3324	1.1069	17	0.2838

Table G.2(b). Between-site contrasts in slope parameter in logistic regression analysis using *log RI* and *Site* as explanatory variables[(1)].

Site 1	m_i	Site 2	m_i	Slope contrast[(2)]	Std. Error	t-stat	df	2-sided p-value
LOL	13	LOM	13	1.1322	1.7720	0.6390	22	0.5294
LOL	13	MCC	9	-2.7002	1.2209	-2.2116	18	**0.0402**
LOL	13	MAC	12	-1.7252	1.3466	-1.2812	21	0.2141
LOM	13	MCC	9	-3.8324	1.5220	-2.5180	18	**0.0215**
LOM	13	MAC	12	-2.8575	1.6245	-1.7590	21	0.0931
MCC	9	MAC	12	0.9750	0.9949	0.9800	17	0.3408

(1) Separate-lines logistic regression model can be expressed as

$$Logit\left(\frac{Y_{ij}}{m_{ij}}\right) = \sum_{i=1}^{n} \alpha_i + \beta_i X_{ij}, \quad j = 1 \text{ to } n_i$$

where

α_i, β_i = intercept and slope parameters, respectively, for logistic regression model

i = index for *Site*

j = index for event (year)

n_i = no. of observations (consecutive pairs of cross section survey dates)

n = no. of sites

Y_{ij} = no. of observed responses (XS's exhibiting change) at Site i for event j

m_{ij} = no. observations (surveyed XS's use in analysis) at Site i for event j

X_{ij} = explanatory variable value (e.g., Q^* or *log RI*) for Site i for event j

(2) Slope contrast is $\beta_{Site2} - \beta_{Site1}$. **Boldface** values are statistically significant at a 95% confidence level.