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.

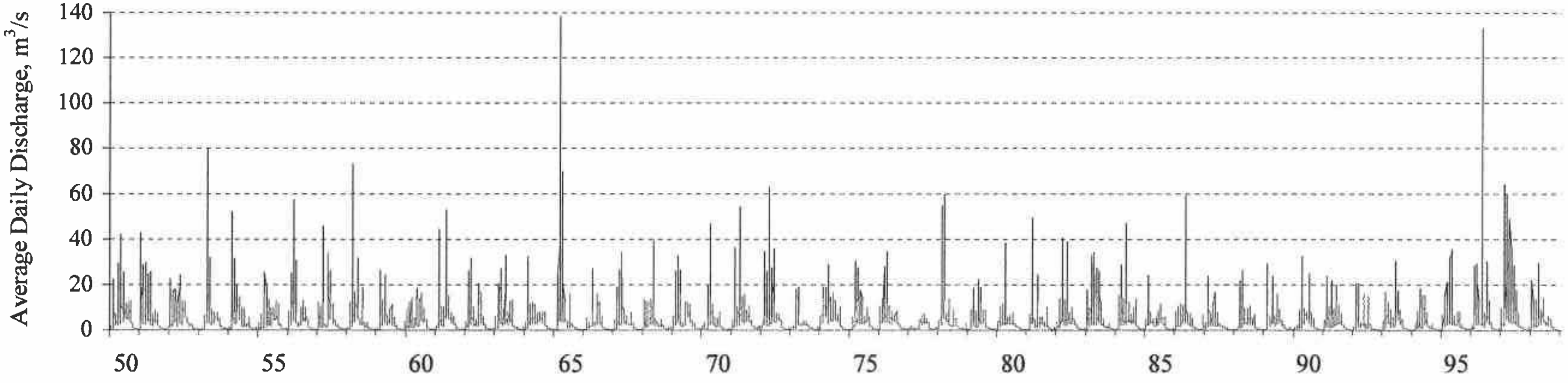
10.1.1 HISTORICAL PEAK FLOWS

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).

(a) average daily discharge



(b) peak flows ≥ 50 m^3/s

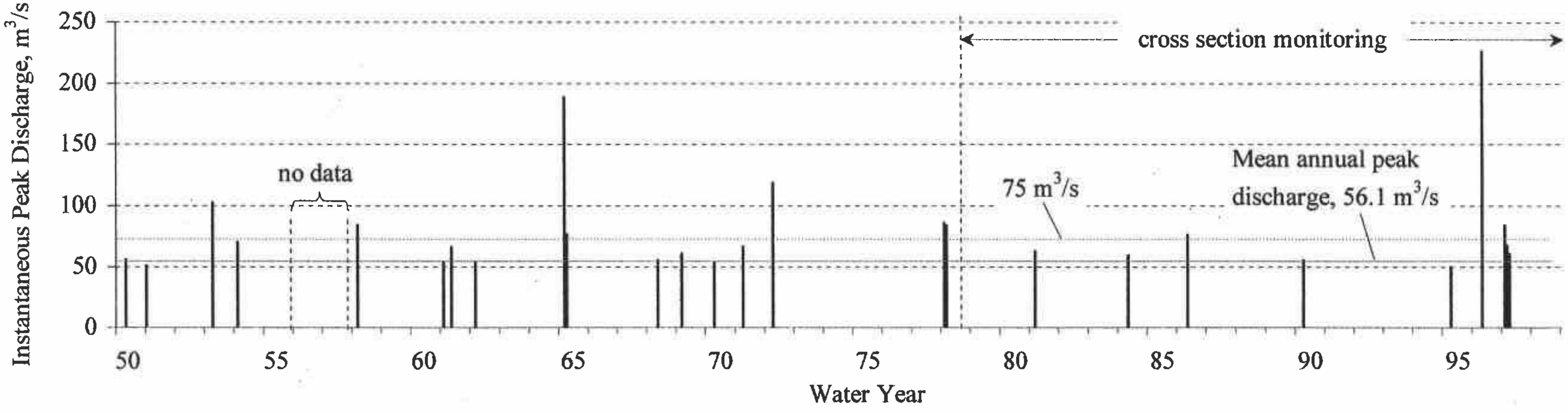


Figure 10.1. Lookout Creek discharge for water years 1950-1998: (a) mean daily discharge, and (b) peak flows exceeding 50 m^3/s (1766 cfs).

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

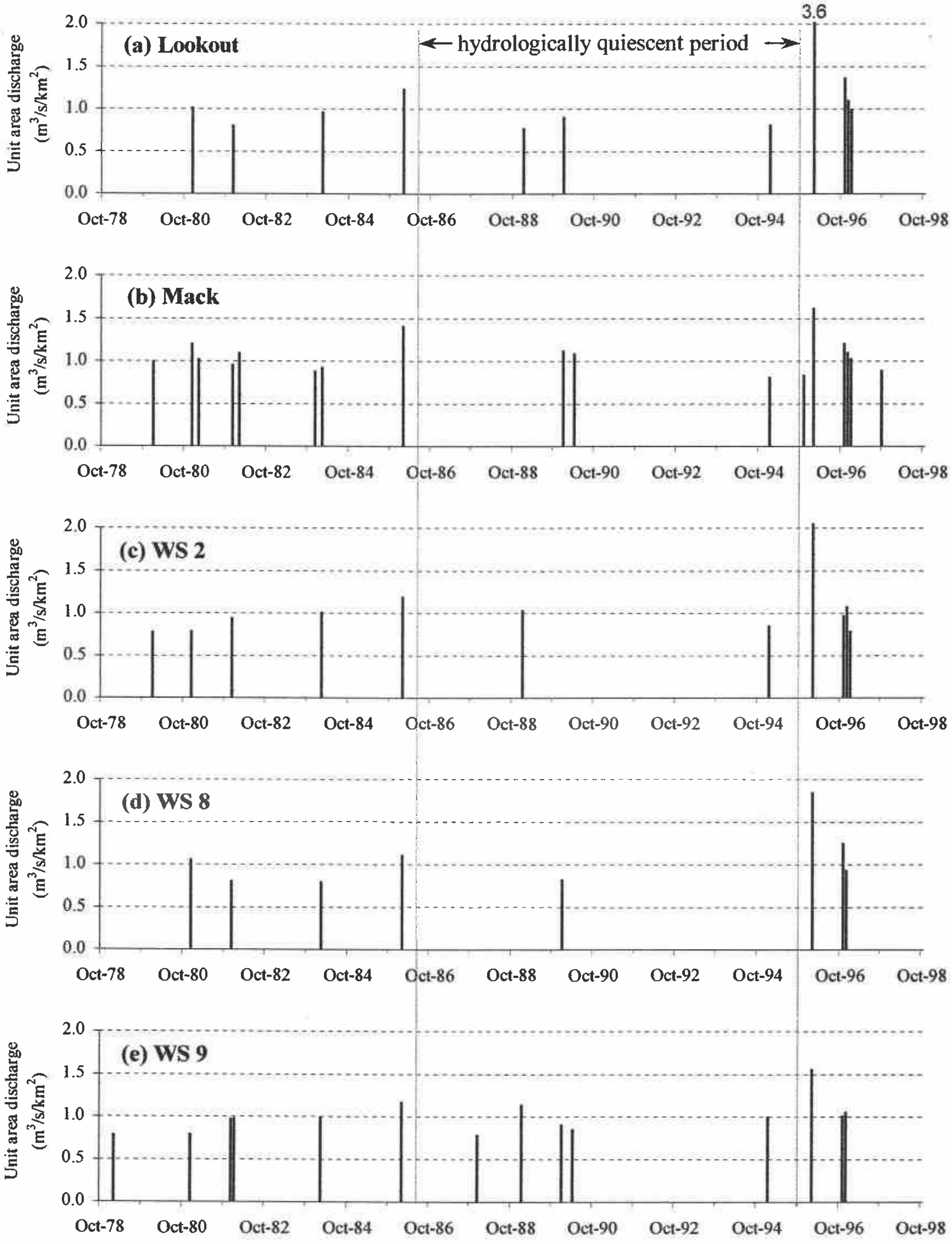


Figure 10.2. Peak flows exceeding 0.75 $m^3/s/km^2$ (equivalent to 46.8 m^3/s or 1,650 cfs at Lookout Creek gauge) during water years 1979–1998 in Lookout Creek and selected small "control" watersheds in the H.J. Andrews Experimental Forest. The hydrographs are arranged in order of decreasing drainage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

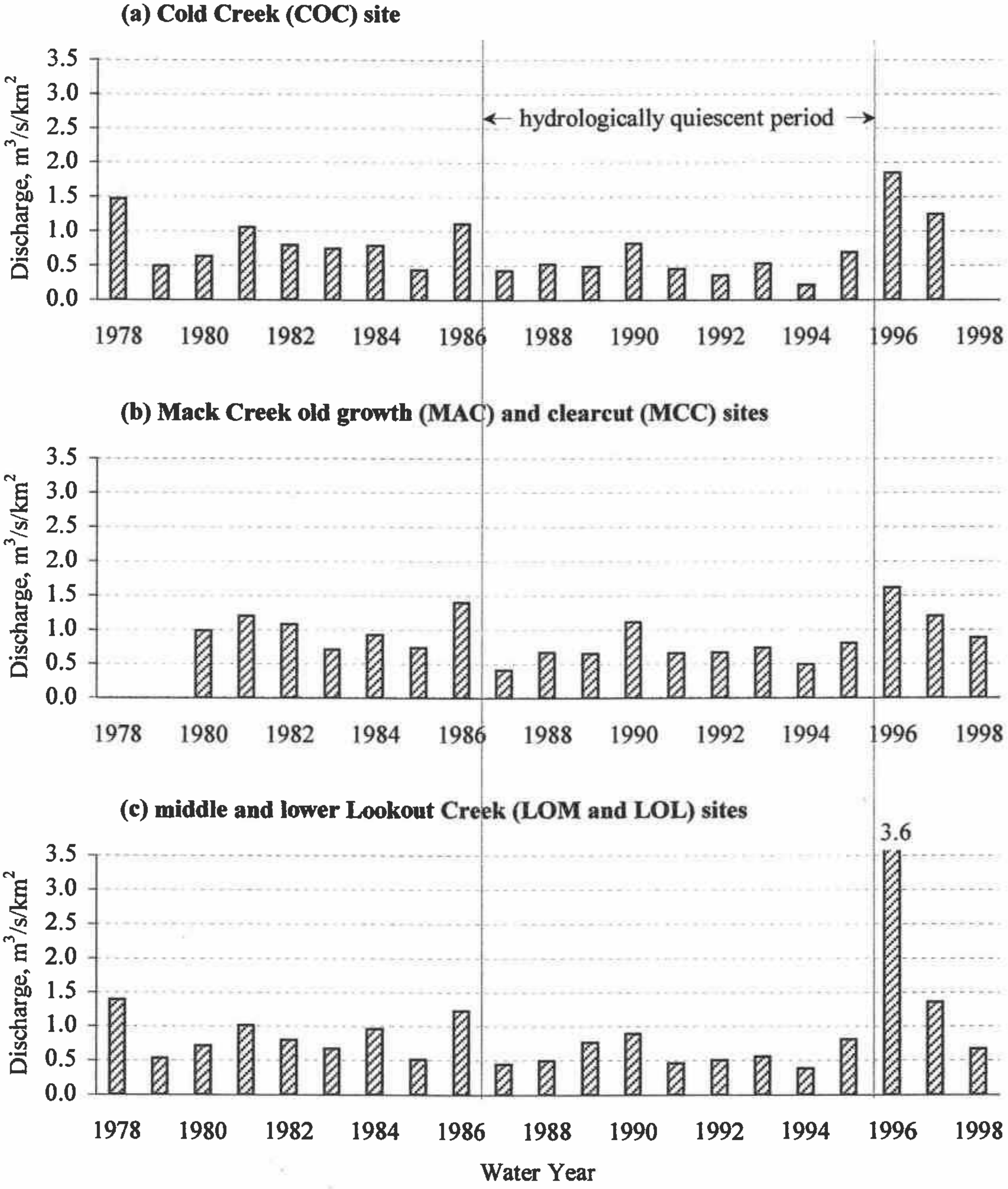


Figure 10.3. Estimated annual maximum instantaneous peak unit area discharge at cross section site locations, 1978-1998: (a) Cold Creek (COC) site, (b) Mack Creek old growth (MAC) and clearcut (MCC) sites, (c) middle and lower Lookout Creek (LOM and LOL) sites.

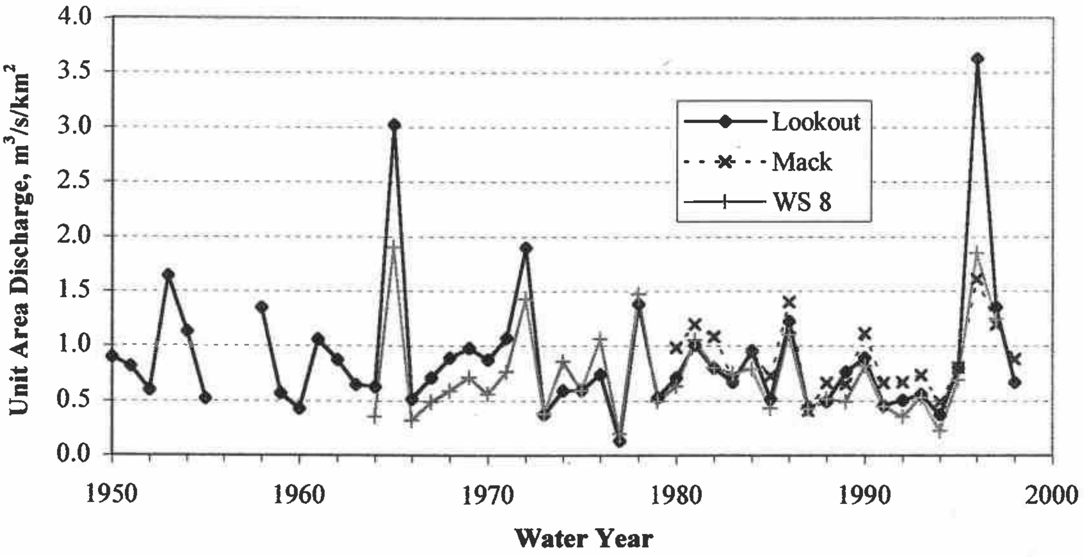


Figure 10.4. Annual peak unit area discharge, Q^*, at selected gaging stations.

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.

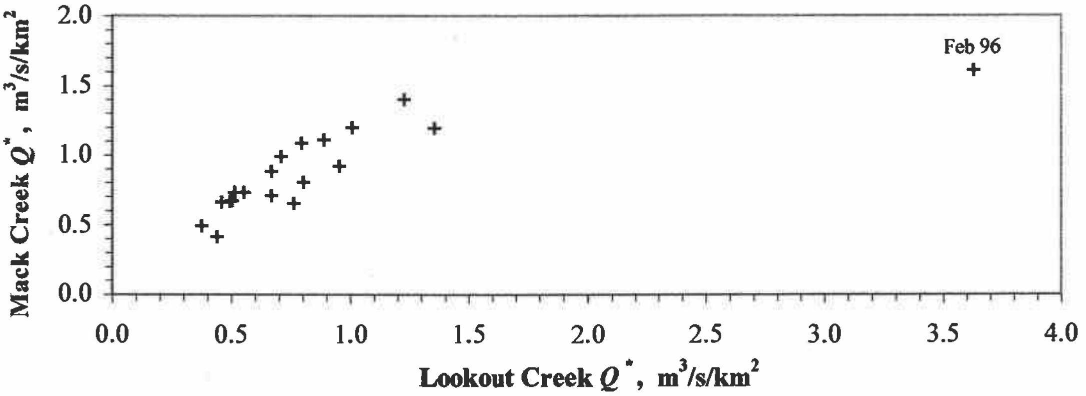
10.1.2 FLOOD FREQUENCY ANALYSIS

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.

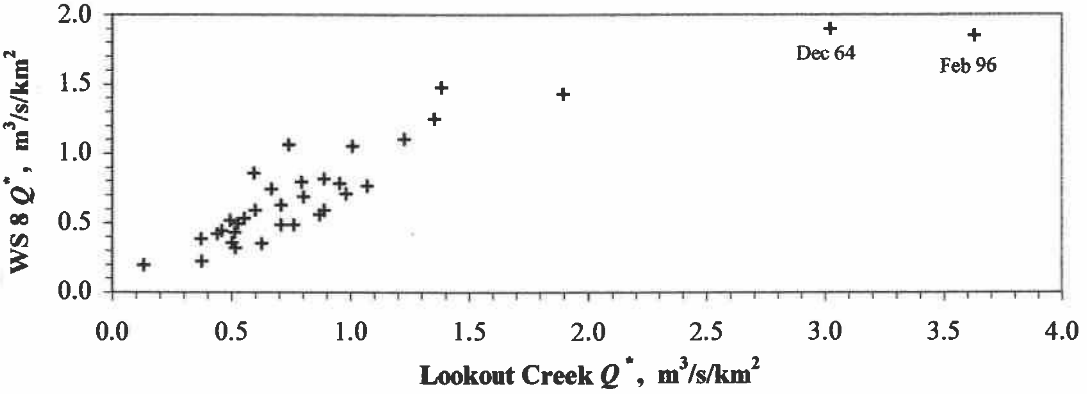
Table 10.1. Annual maximum instantaneous peak flows and estimated recurrence intervals (RI) for cross section sites, WY 1978-1998. Values in **boldface** indicate events for which the estimated RI is 5 years or greater.

	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	

(a) Mack Ck. vs. Lookout Ck., 1980-98



(b) WS 8 vs. Lookout Ck., 1964-97



(c) WS 8 vs. Mack Ck., 1980-97

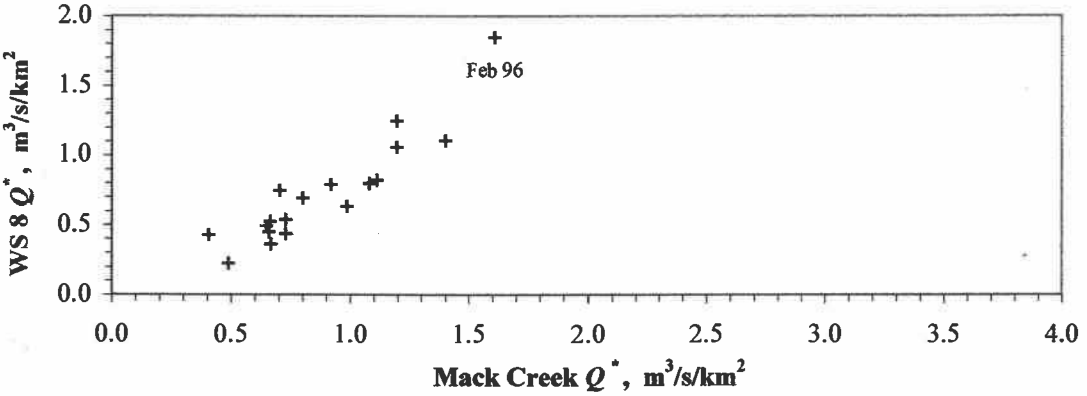


Figure 10.5. Scatterplots of magnitude of annual peak flows (as unit area discharge) for selected gaging station pairs: (a) Mack Ck. vs. Lookout Ck., 1980-98; (b) WS 8 vs. Lookout Ck., 1964-97; (c) WS 8 vs. Mack Ck., 1980-97. Major floods of Dec. 1964 and Feb. 1996 were relatively larger events in Lookout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

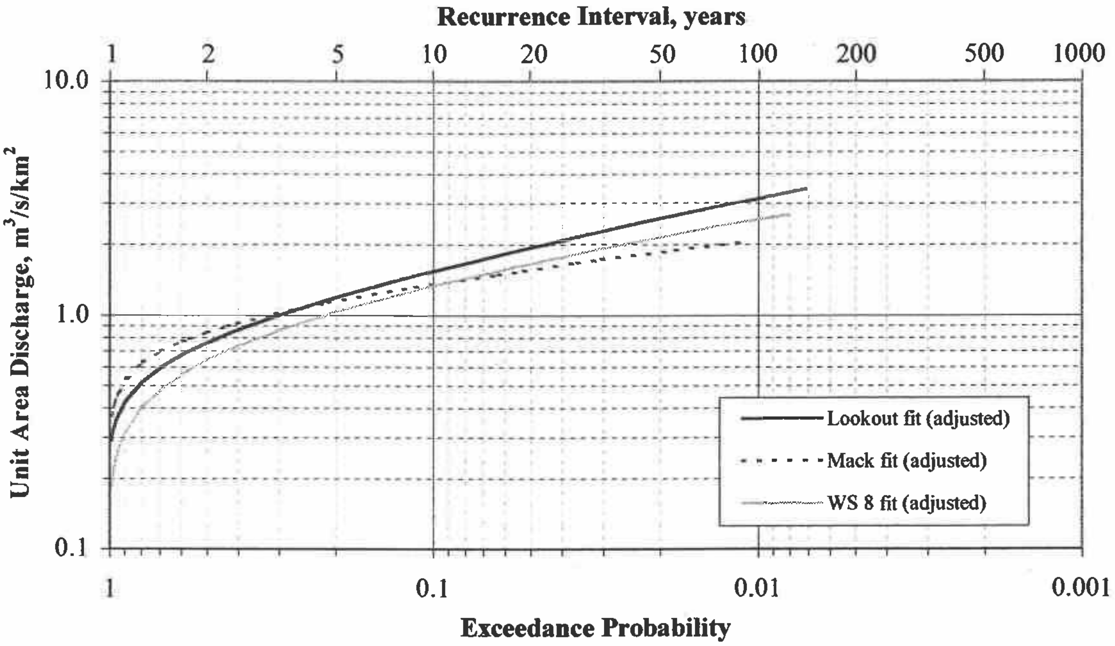


Figure 10.6. Frequency plots for annual maximum instantaneous peak flows in Lookout Creek, Mack Creek, and WS 8, showing fitted Log Pearson Type III curves with expected probability adjustment.

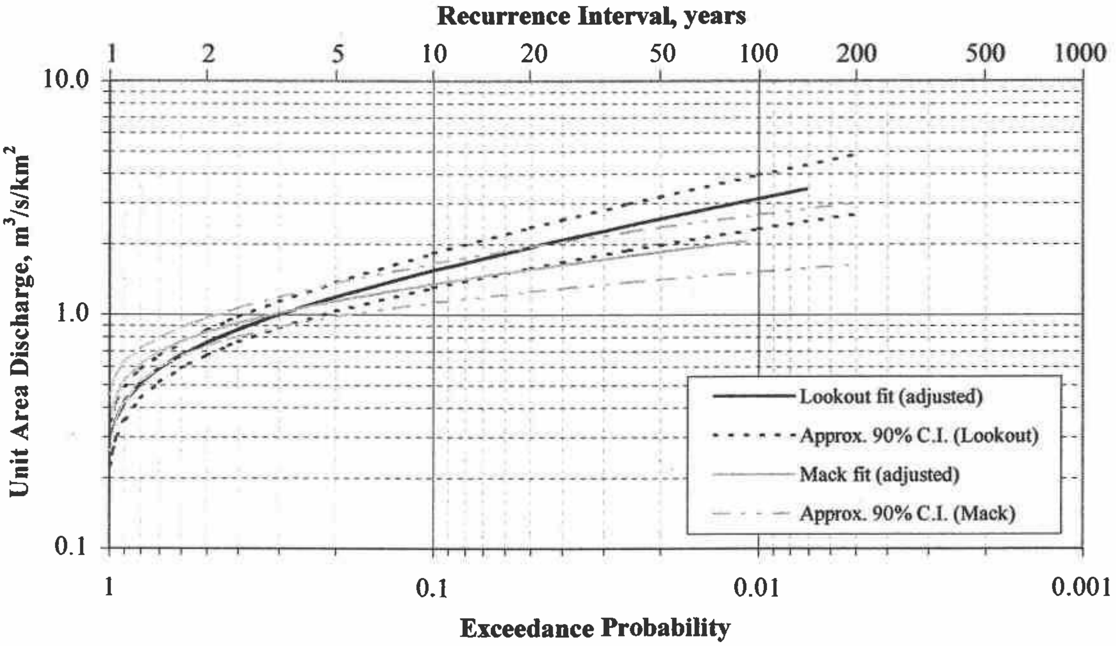


Figure 10.7. Frequency plots for annual maximum instantaneous peak flows in Lookout and Mack Creeks showing fitted Log Pearson Type III curves (with expected probability adjustment) and approximate 90% confidence intervals.

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.

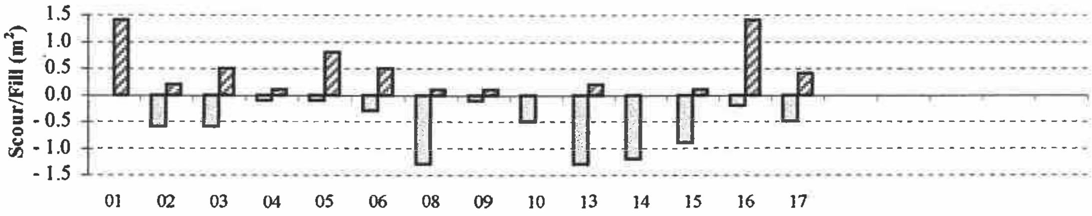
Channel response to the February 1996 and February 1986 floods at each of the cross sections sites are described in greater detail in Sections 10.2.1 through 10.2.4.

10.2.1 COLD CREEK SITE

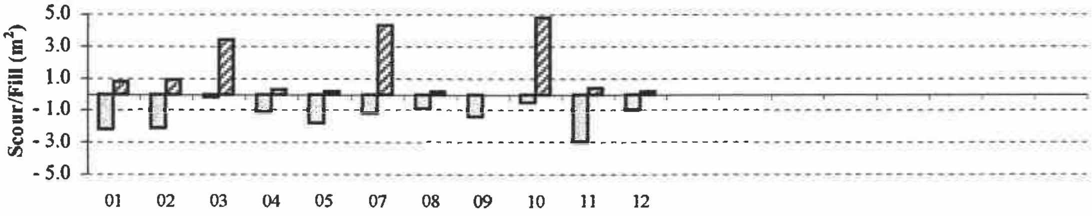
In 1996, 12 of 13 cross sections for which change could be quantified at the COC site experienced significant change, with scour dominating in most of the upstream part of the reach and deposition dominating downstream (Figure 10.8[a]), but no discernible disturbance of the riparian zone. These 12 cross 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).

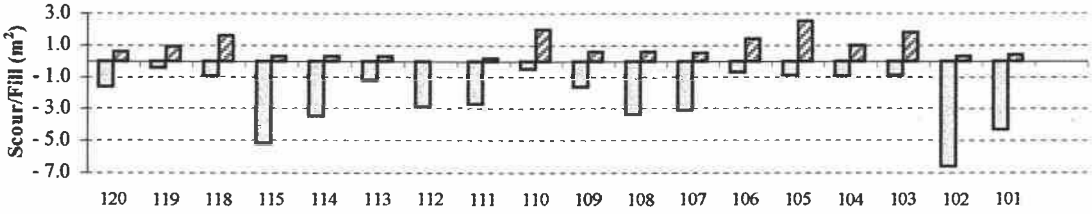
(a) Cold Creek (COC)



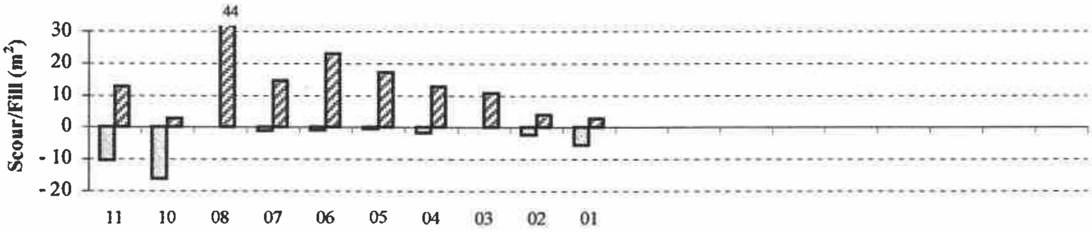
(b) Mack Creek Old Growth (MAC)



(c) Mack Creek Clearcut (MCC)



(d) Middle Lookout Creek (LOM)



(e) Lower Lookout Creek (LOL)

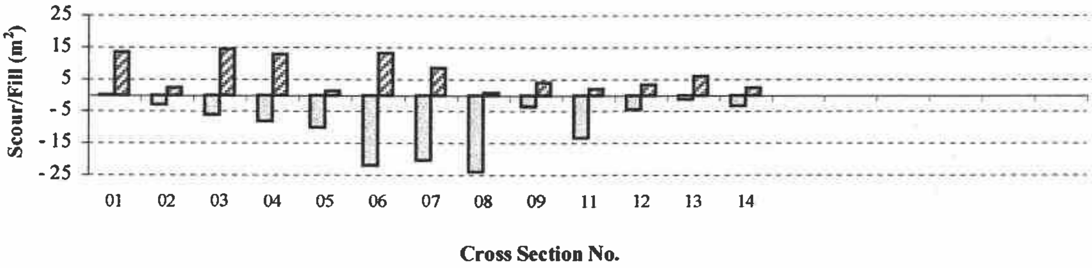


Figure 10.8. (continued)

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).

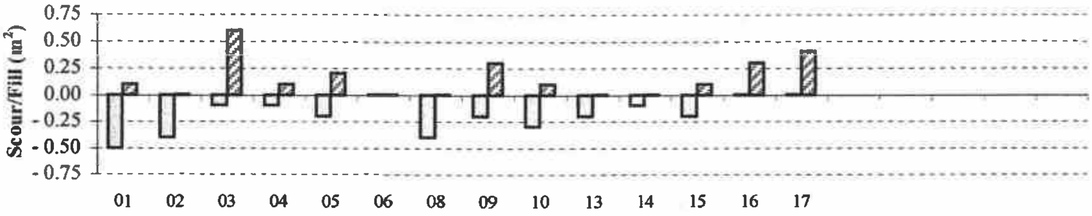
In contrast, cross section data revealed only very minor, patchy scour and fill at the Cold Creek site in response to the February 1986 flood. Only two cross sections exhibited scour (XS 1) or deposition (XS 3) of 0.5 m^2 or greater (Figure 10.9[a]). Scour at four cross sections (XS 1, 2, 8 and 10) exceeded 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

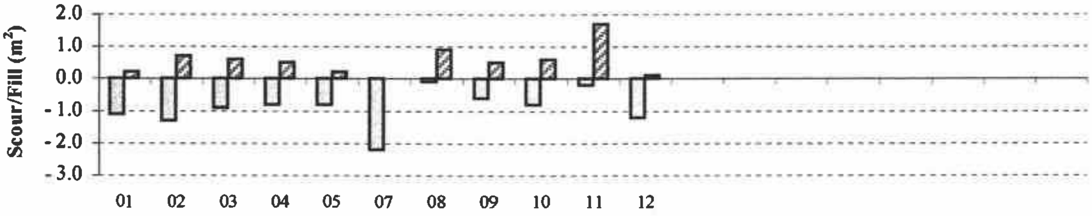
In 1996, the Mack Creek old-growth (MAC) site experienced patchy scour and deposition, but the riparian zone experienced little disturbance (Figure 10.8[b]). Three widely spaced cross sections (XS 3, 7, and 10)—each of which is located just

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).

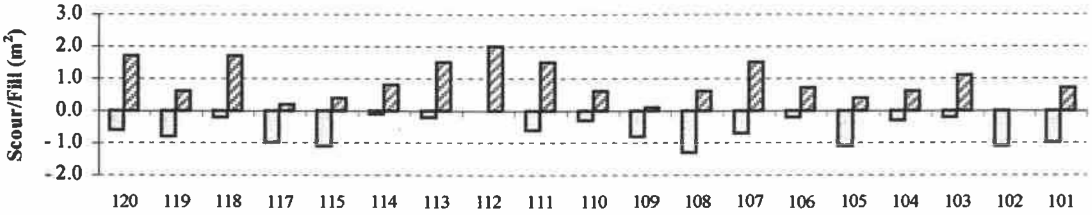
(a) Cold Creek (COC)



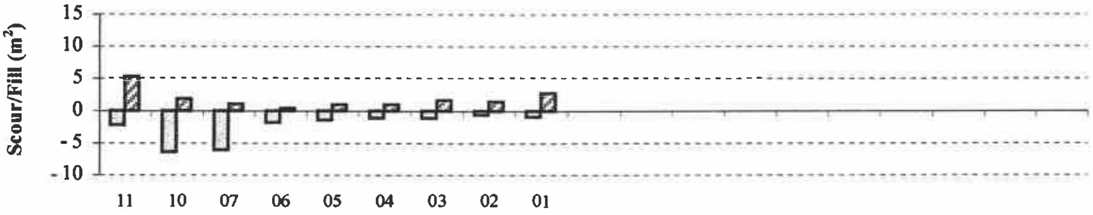
(b) Mack Creek Old Growth (MAC)



(c) Mack Creek Clearcut (MCC)



(d) Middle Lookout Creek (LOM)



(e) Lower Lookout Creek (LOL)

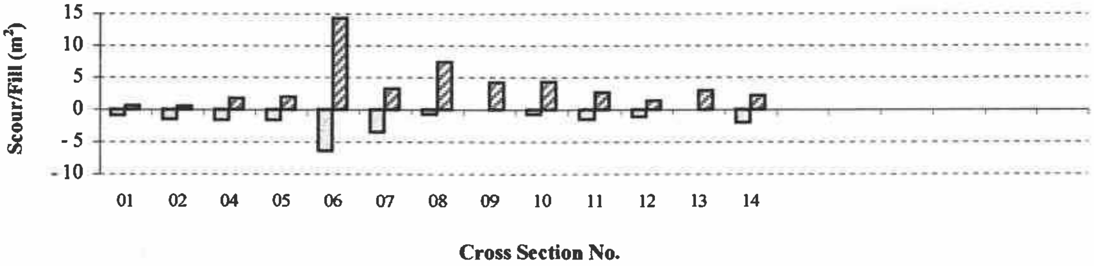


Figure 10.9. (continued)

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

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[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)

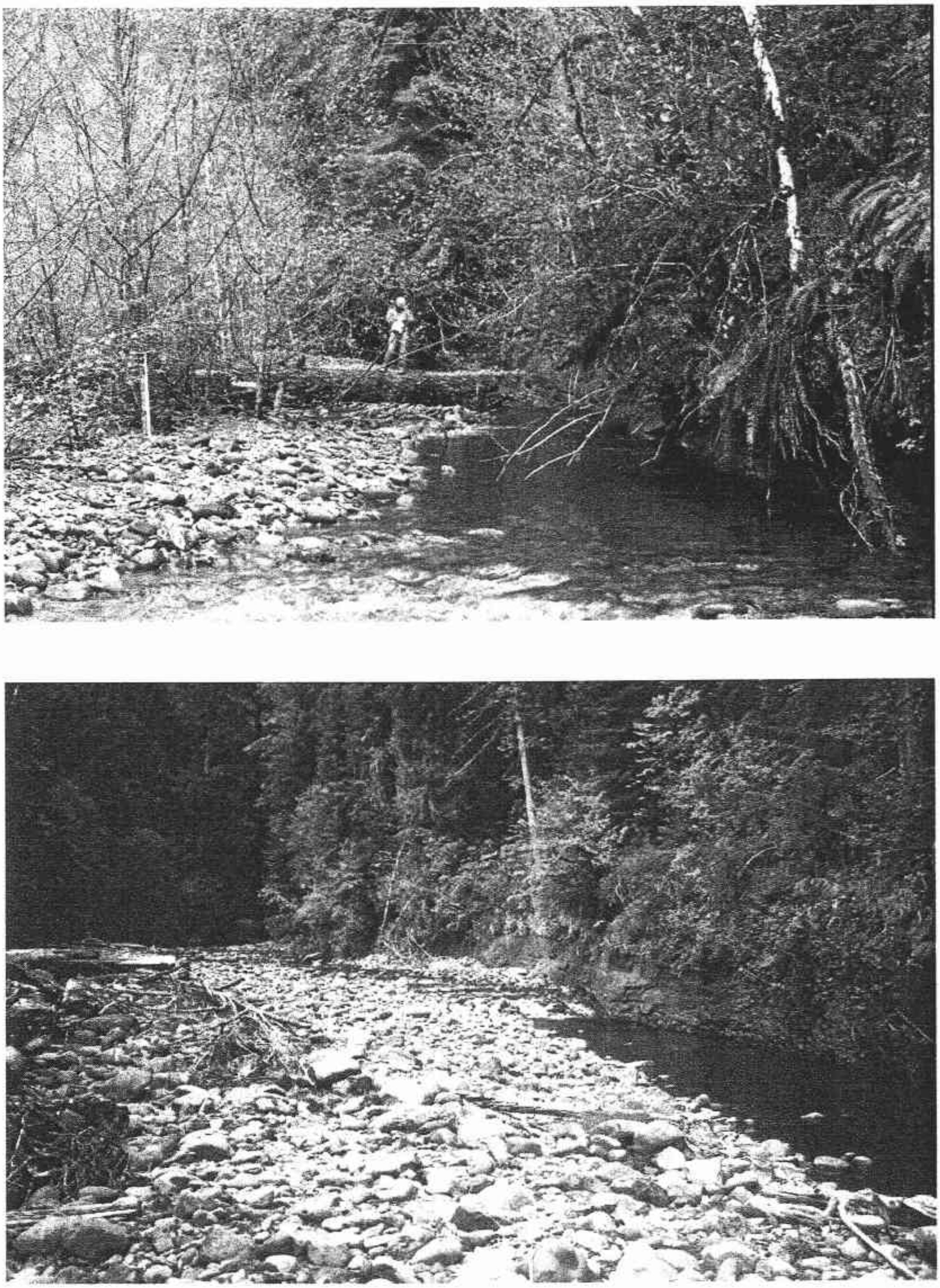


Figure 10.11. View upstream along east bank of LOL site: (a) end of spanner logs between XS 7 and XS 8 in 1986 (same logs as in Figure 10.10 [a]); (b) same area viewed from slightly farther downstream in 1997. Channel was incised by 1.5 to 2 m on east bank during the February 1996 flood; note position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

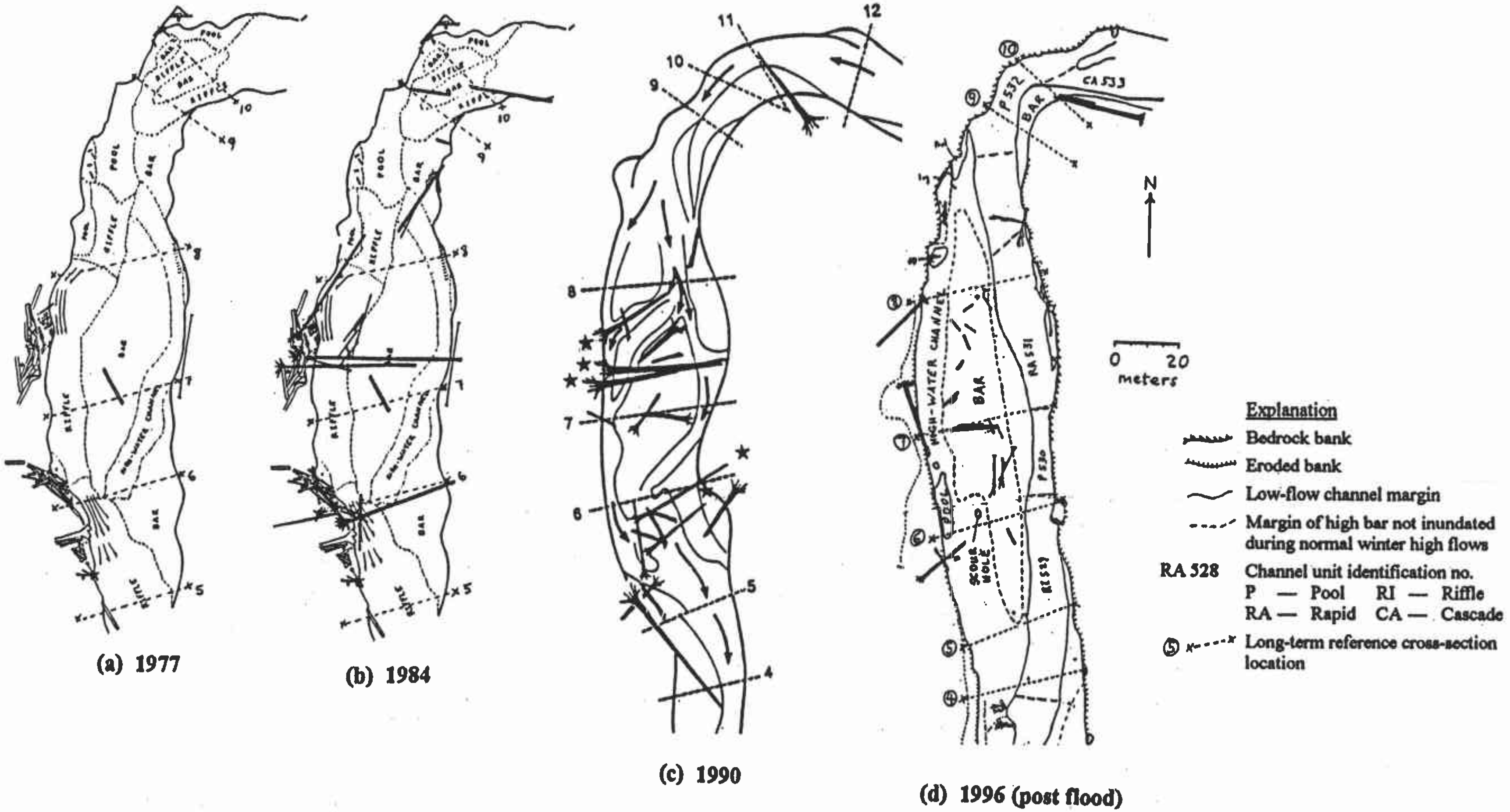
Downstream of the large central bar, approximately 6 m of bank retreat occurred at XS 4 and 10 m at XS 5 occurred along the right bank. In this area, an approximately 6- to 12-m wide patch of floodplain forested with alders and maples—including some mature bigleaf maples—was removed during the 1996 flood, 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



(a) 1977

(b) 1984

(c) 1990

(d) 1996 (post flood)

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]).

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

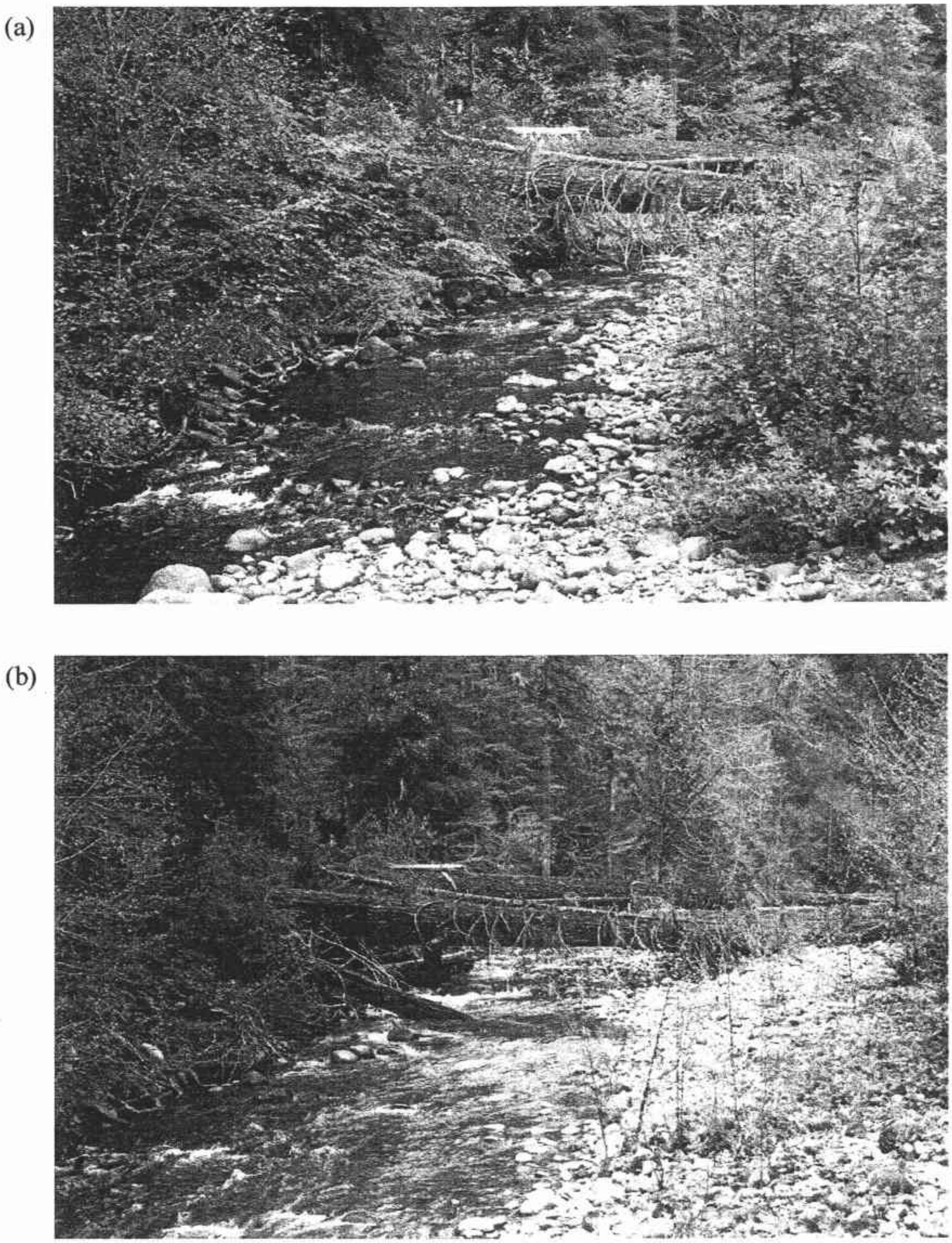


Figure 10.13. View upstream along west bank of LOL site from XS 6: (a) 1985, (b) 1986. Modest channel changes ascribed to the February 1986 flood include bank and channel scour (note the exposed roots and apparently deeper thalweg in the left foreground of [b]), input of new logs beneath large spanner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

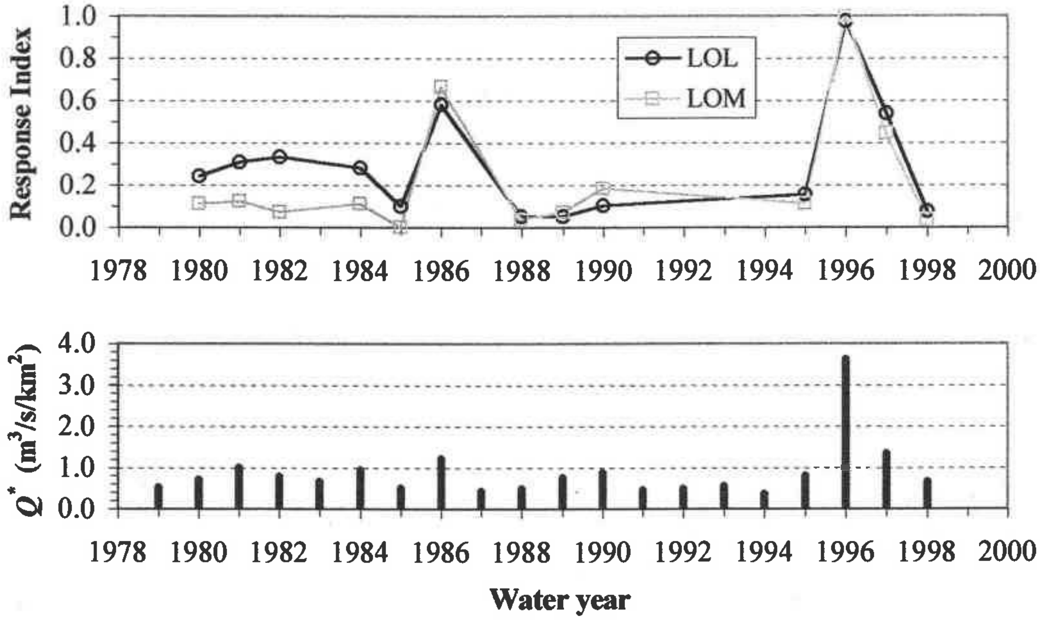
As previously described, the flood of February 1996 essentially completely reset the channel, resulting in a straightened, simplified channel morphology (compare Figures 10.12 [c] and [d]). The flood removed most of the LWD from the channel, including all of the channel-spanning logs. The log on the 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

(a) Lookout Creek sites (LOL and LOM)



(b) Mack Creek sites (MCC and MAC)

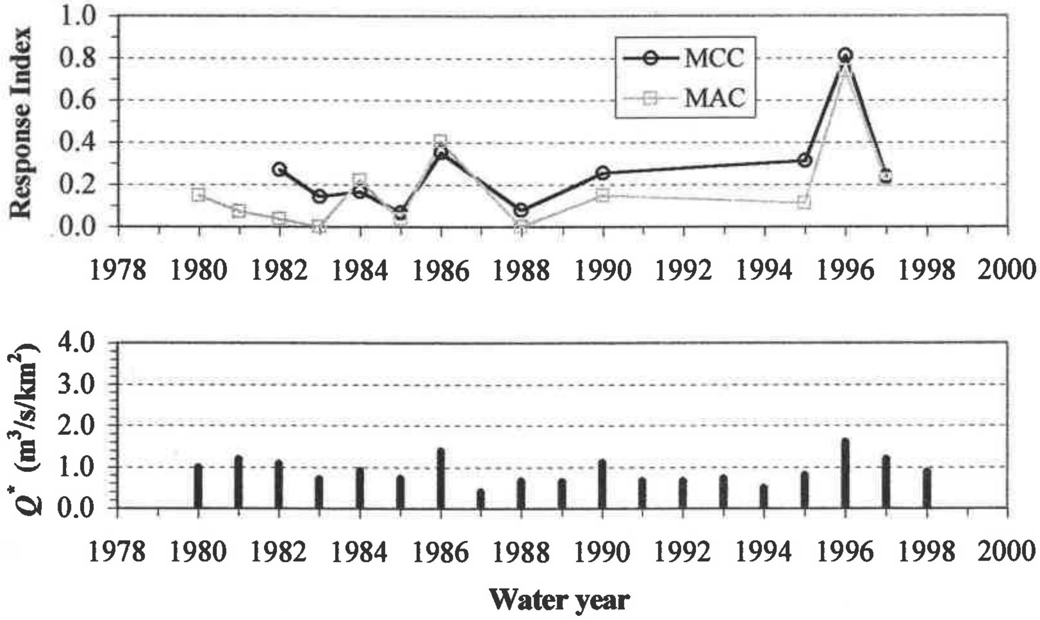
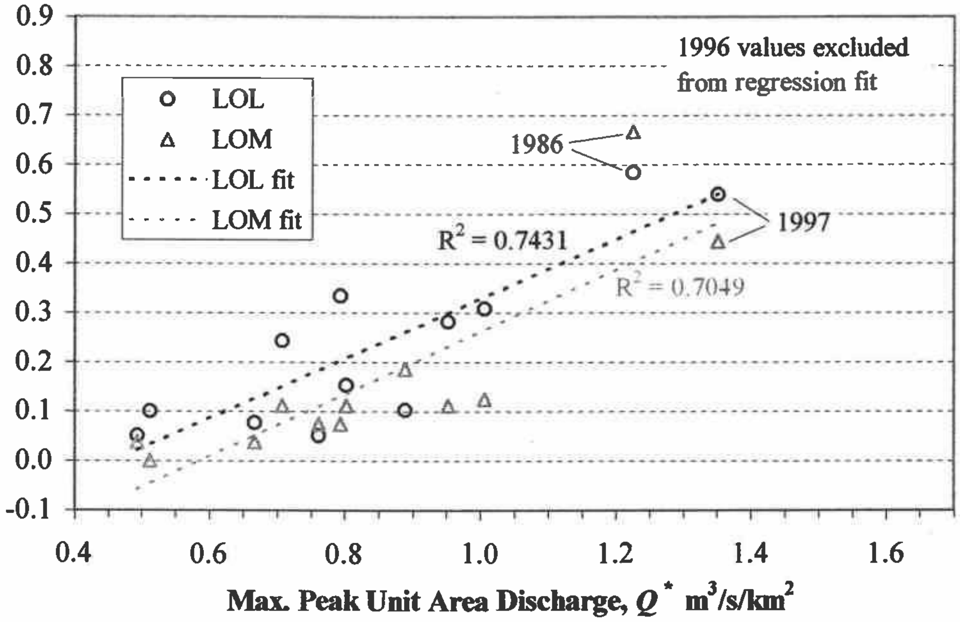


Figure 10.14. Cross section response index scores and maximum instantaneous peak unit area discharge (Q^*) for (a) Lookout Creek sites (LOL and LOM), and (b) Mack Creek sites (MCC and MAC).

(a) Lookout Creek sites



(b) Mack Creek sites

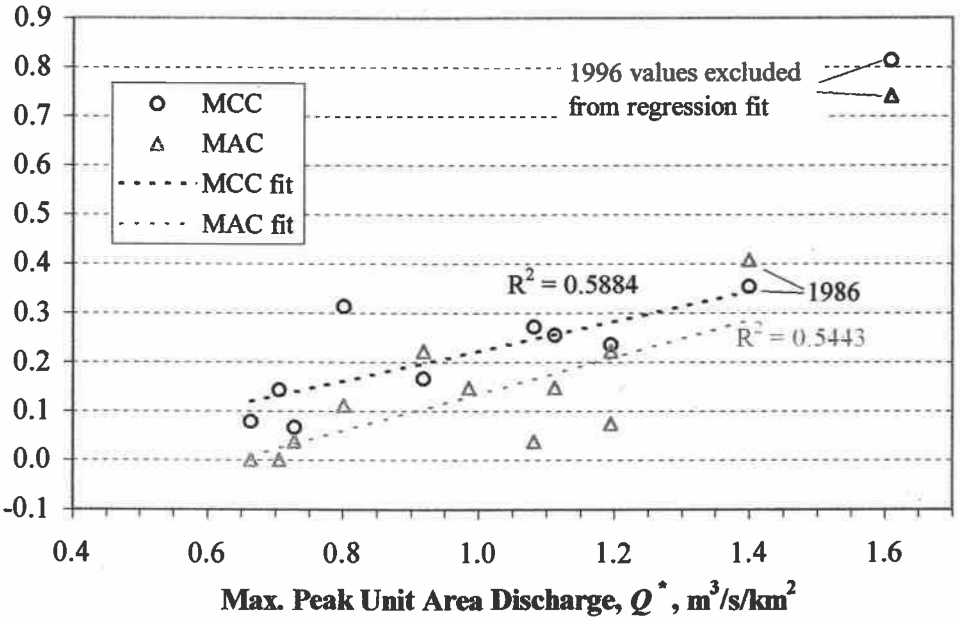


Figure 10.15. Scatter plots of cross section response index scores vs. maximum peak unit area discharge, Q^*, for (a) Lookout Creek sites, and (b) Mack Creek sites. The 1996 flood has been omitted from the Lookout Creek plots so that these can be shown at the same scale as the Mack Creek plots.

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,

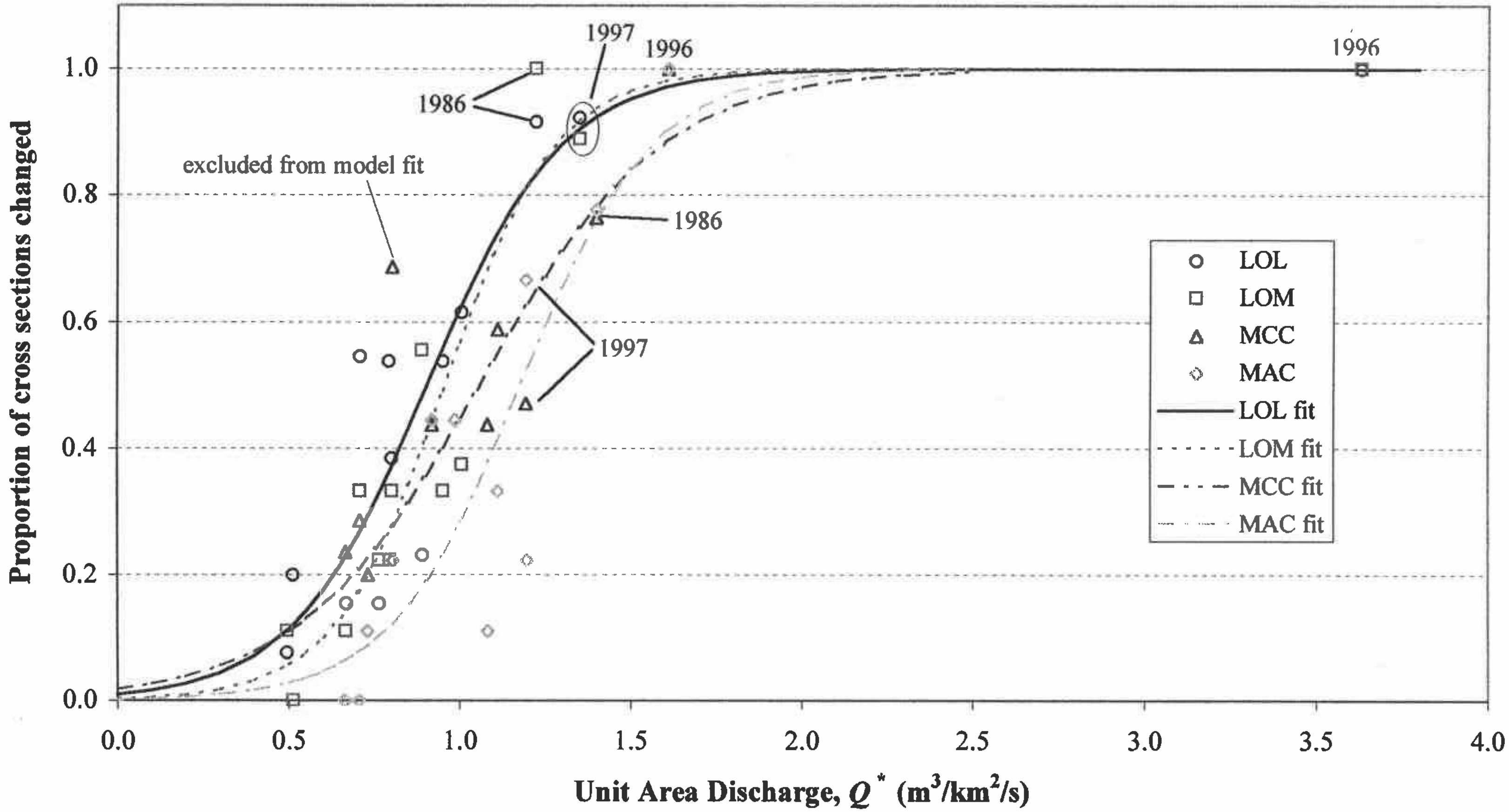


Figure 10.16. Proportion of cross sections exhibiting change versus maximum instantaneous peak unit area discharge during the interval since the previous cross section survey for Lookout and Mack Creek sites. Lines show fitted quasi-likelihood logistic regression model. One outlier (1995 data point for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

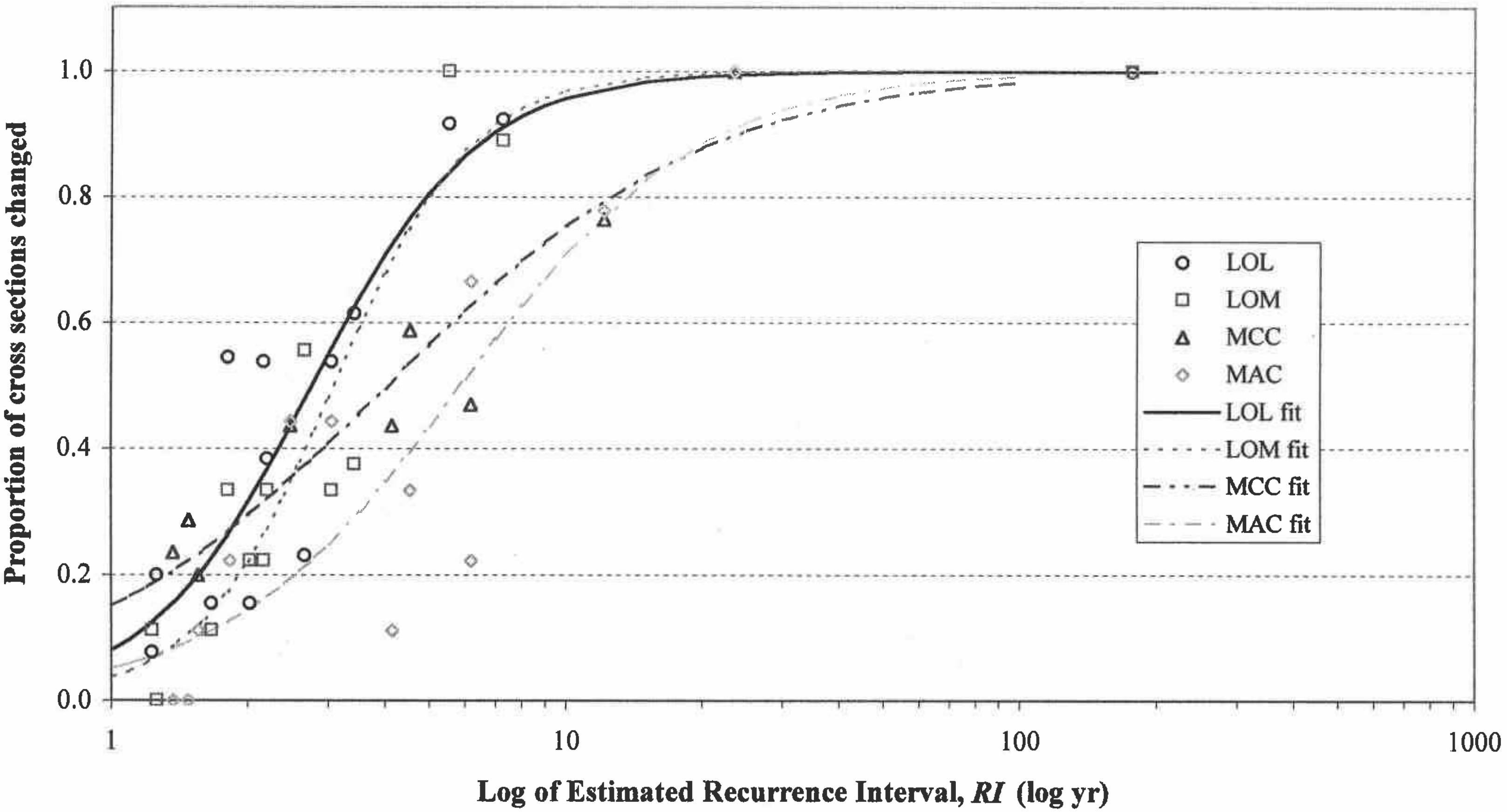


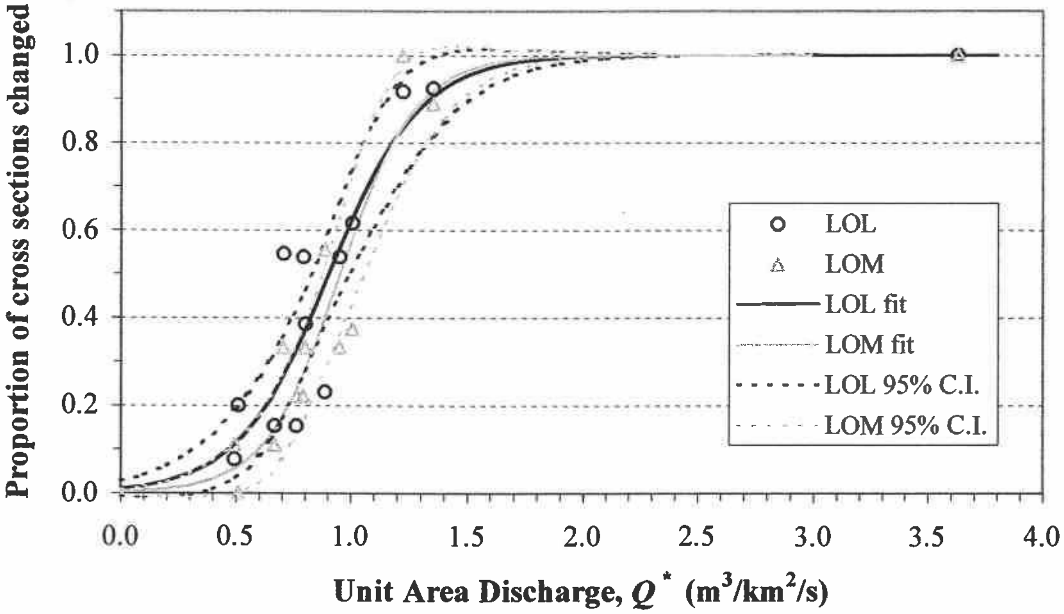
Figure 10.17. Proportion of cross sections exhibiting change versus estimated recurrence interval of maximum instantaneous peak discharge for Lookout and Mack Creek sites. Lines give quasi-likelihood logistic regression fit (using log (*RI*) and *Site* as explanatory variables.

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

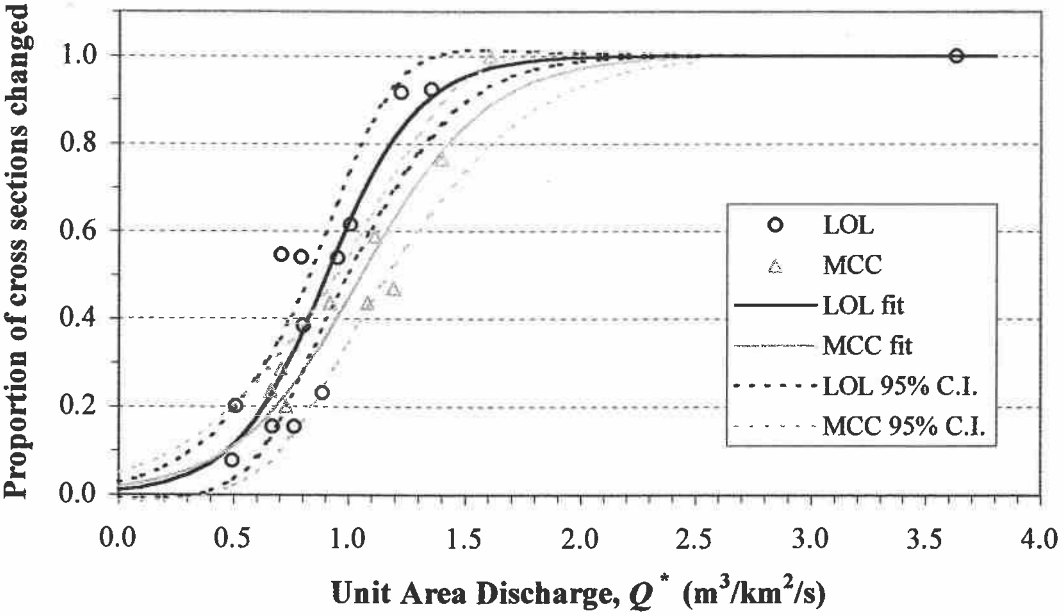
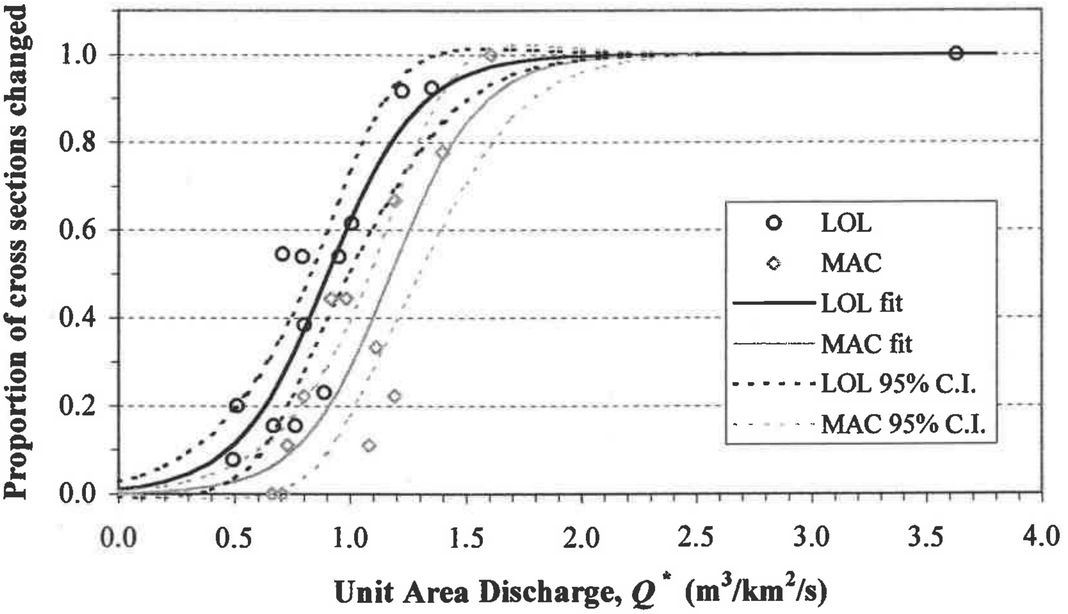


Figure 10.18. Proportion of cross sections exhibiting change versus maximum instantaneous peak unit area discharge for (a) LOL vs. LOM, (b) LOL vs. MCC, (c) LOL vs. MAC, (d) LOM vs. MCC, (e) LOM vs. MAC, and (f), MCC vs. MAC sites. Solid lines show quasi-likelihood logistic regression fit; dashed lines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

(c) LOL vs. MAC



(d) LOM vs. MCC

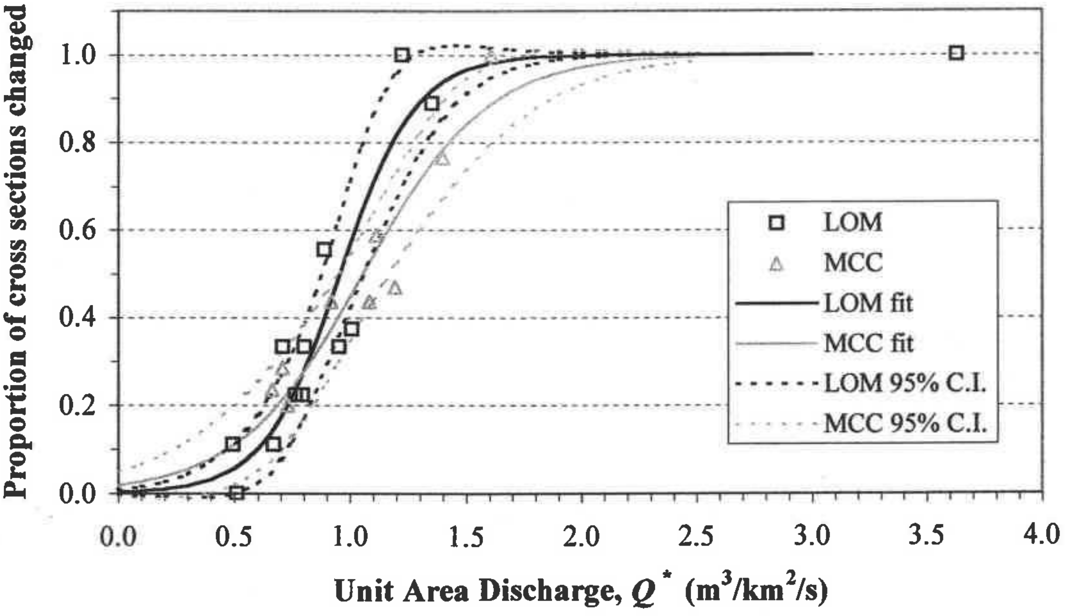
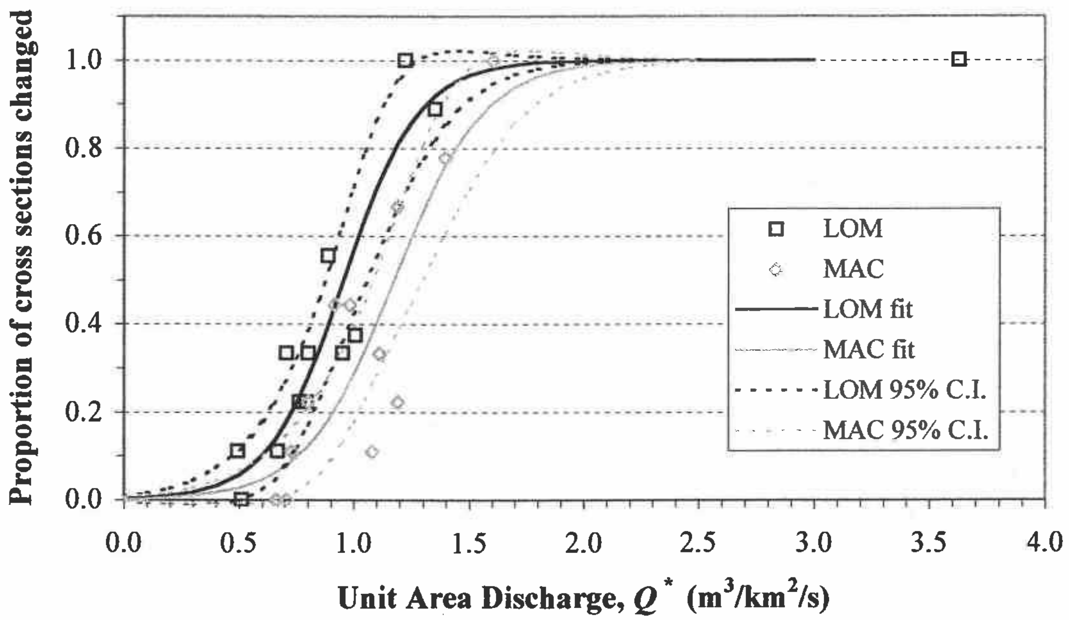


Figure 10.18 (continued)

(e) LOM vs. MAC



(f) MCC vs. MAC

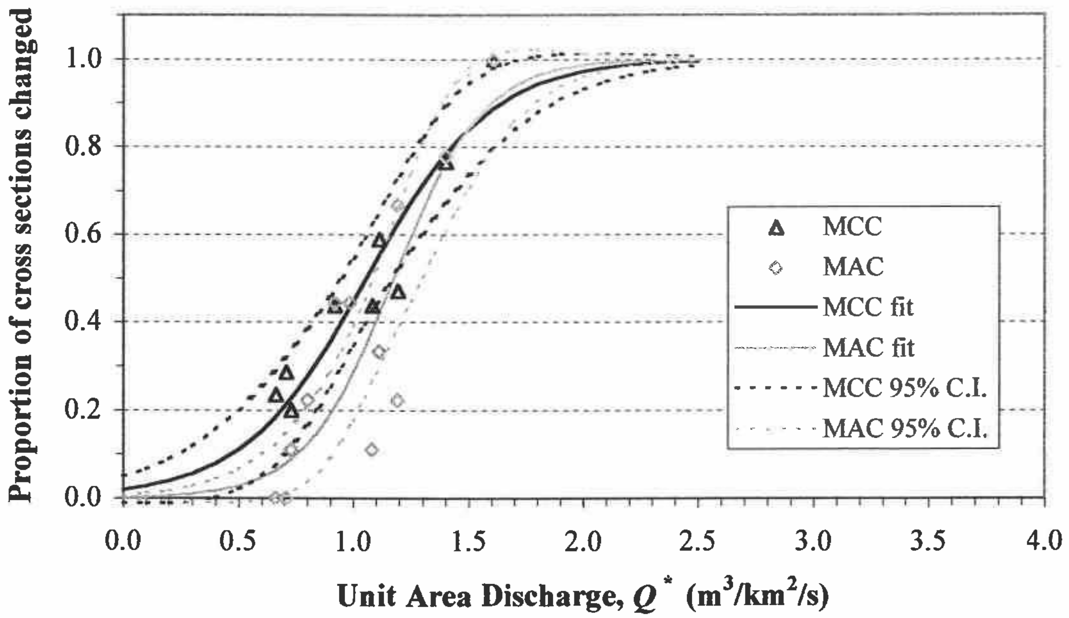


Figure 10.18 (continued)

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.

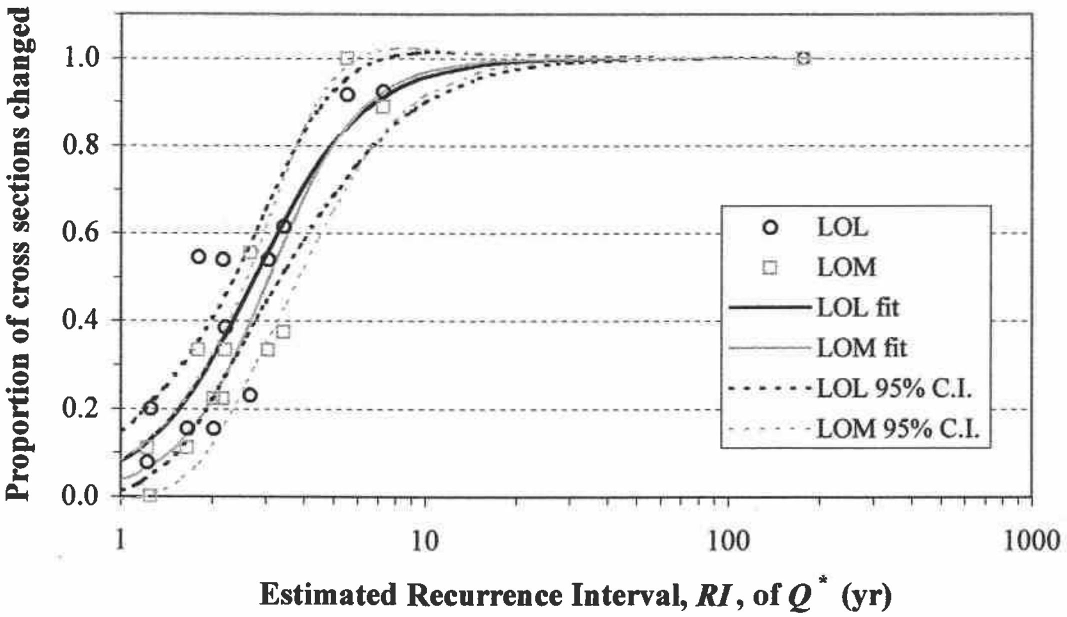
Site	$\beta^{(1)}$	Std. Err.	df	Odds ratio for doubling of recurrence interval$^{(3)}$ mean	LCL	UCL
LOL	5.56	1.076	11	5.3	2.6	10.9
LOM	6.69	1.408	11	7.5	2.9	19.0
MCC	2.86	0.578	7	2.4	1.6	3.6
MAC	3.83	0.810	10	3.2	1.8	5.5

(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

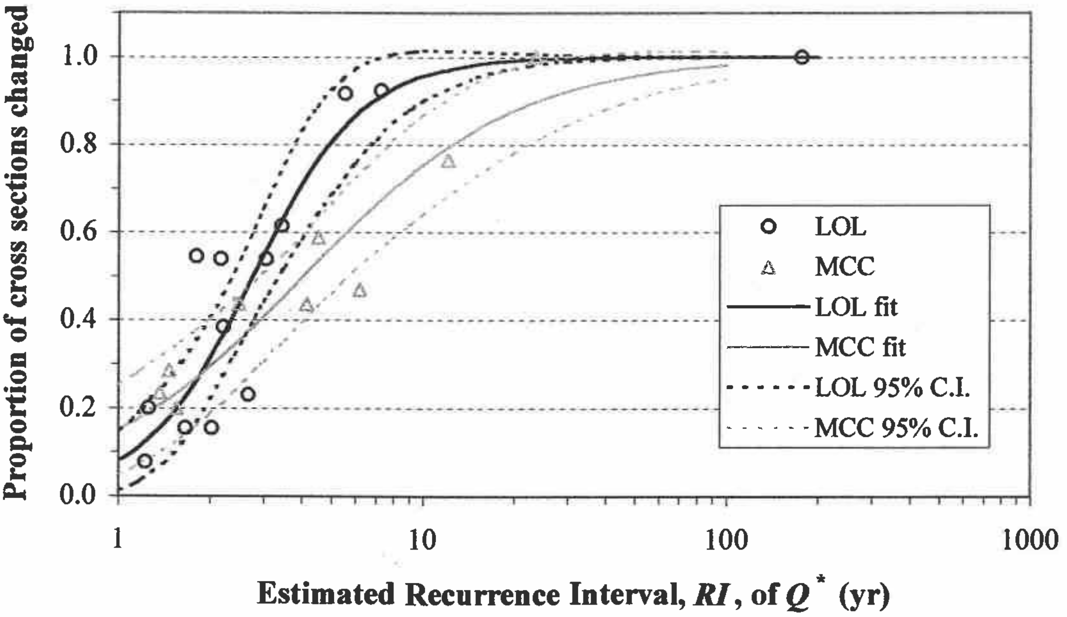
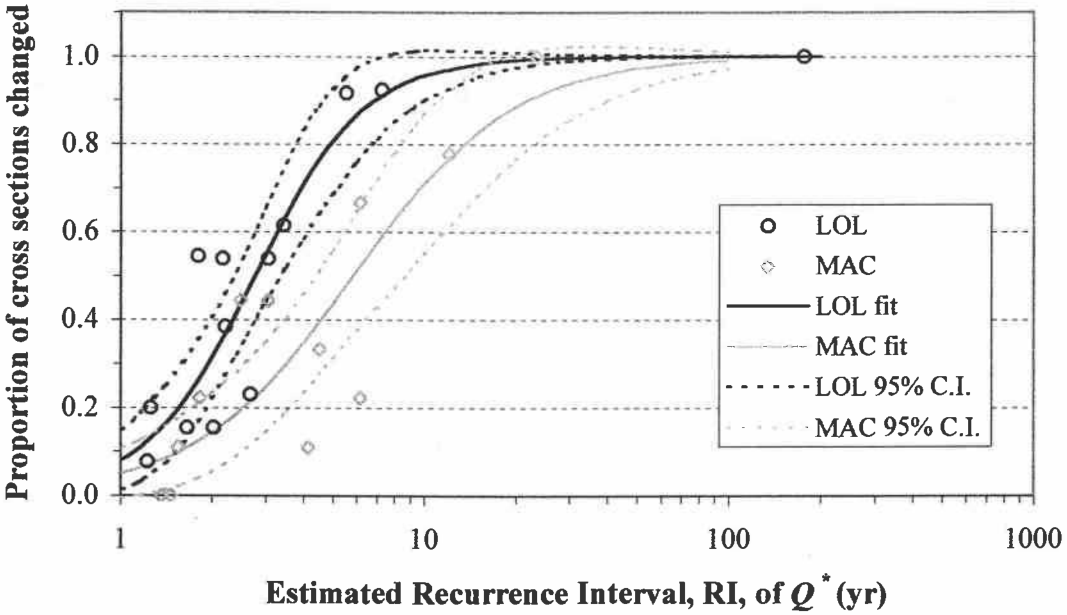


Figure 10.19. Proportion of cross sections exhibiting change versus estimated recurrence interval (RI) of maximum instantaneous peak discharge (Q^*) for (a) LOL vs. LOM and (b) LOL vs. MCC, (c) LOL vs. MAC, (d) LOM vs. MCC, (e) LOM vs. MAC, and (f) MCC vs. MAC sites. Solid lines give quasi-likelihood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

(c) LOL vs. MAC



(d) LOM vs. MCC

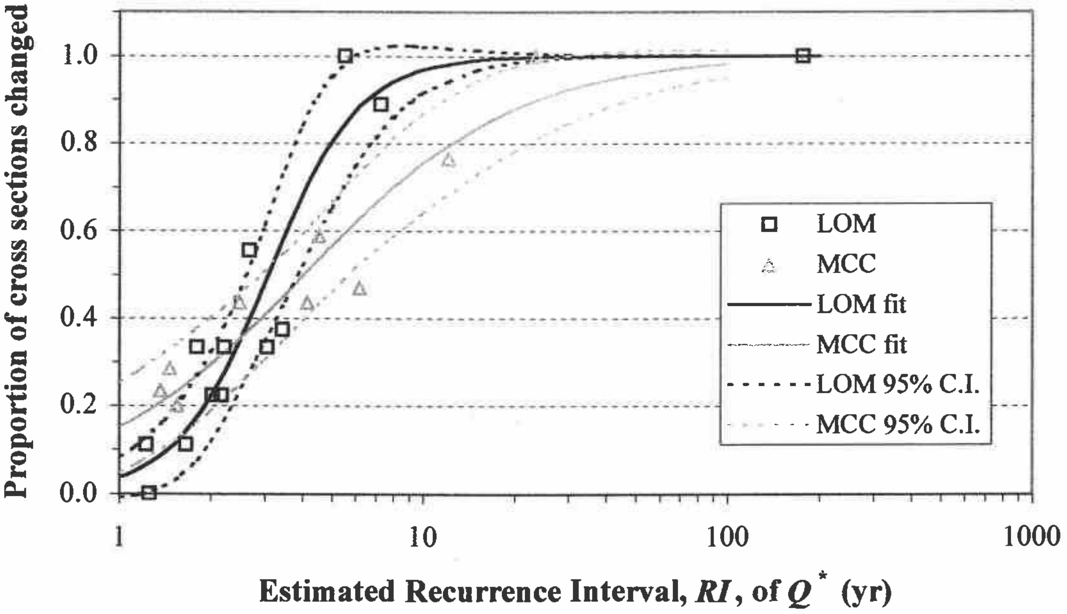
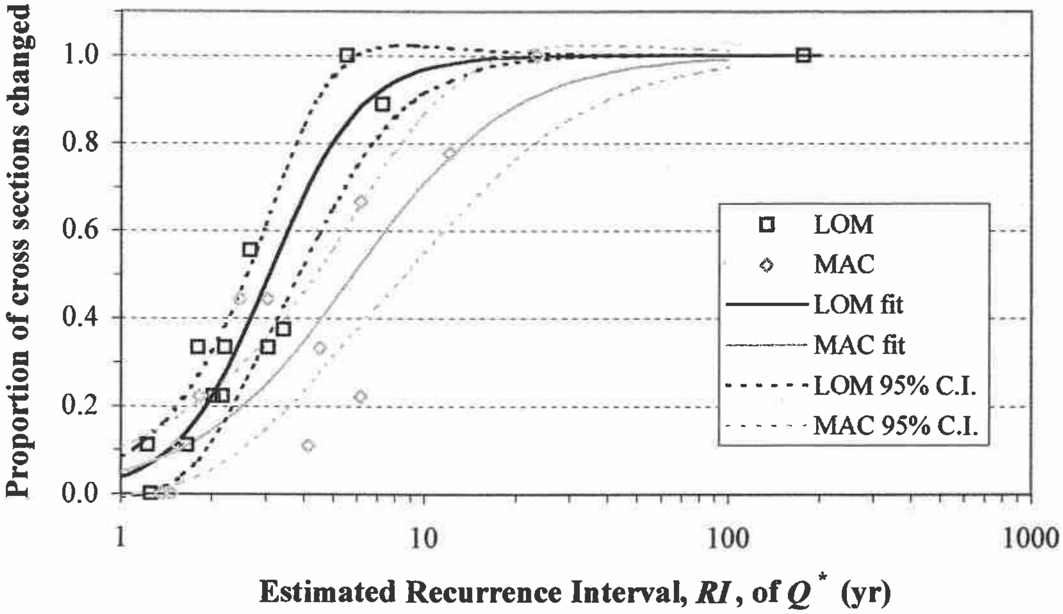


Figure 10.19 (continued)

(e) LOM vs. MAC



(f) MCC vs. MAC

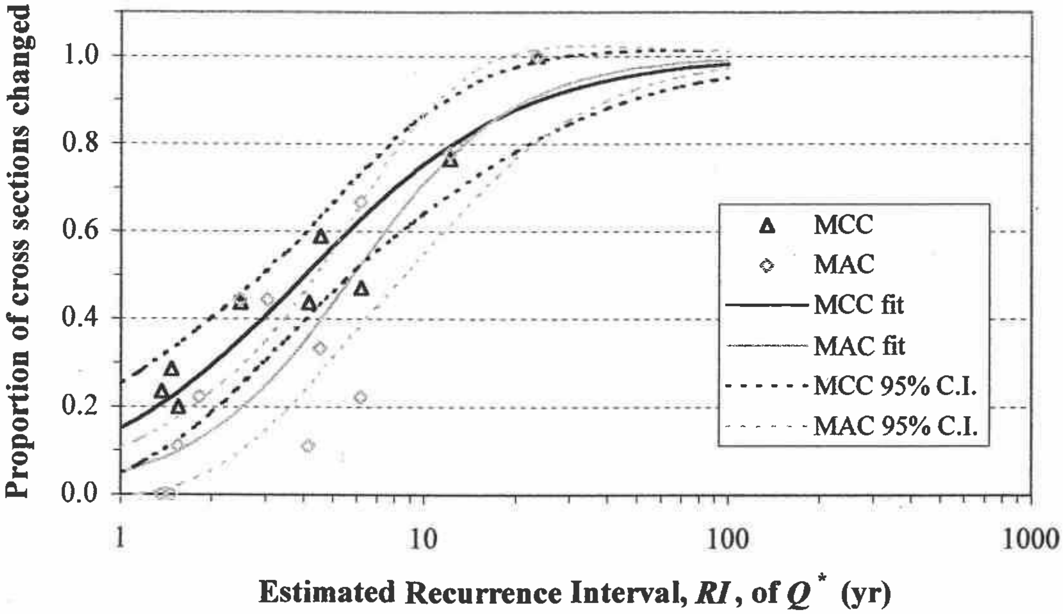


Figure 10.19 (continued)