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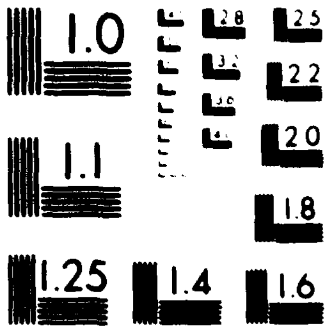

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GEOMORPHIC RESPONSE OF FALL RIVER FOLLOWING THE LAWN LAKE FLOOD, ROCKY MOUNTAIN NATIONAL PARK, COLORADO

Final Report, Contract No. DAAG29-85-K-0108
Department of the Army
United States Army Laboratory Command
Army Research Office

by

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The 4-year Fall River data set represents a unique study of a catastrophically-effected stream. The results of this work provide important insight into the short- term rates and mechanisms of geomorphic response following large flood events.

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INTRODUCTION

Problem Statement

Following the Lawn Lake flood, July 15, 1982, in Rocky Mountain National Park, geomorphic process studies were initiated on Fall River in Horseshoe Park (Fig. 1). This event has provided an ideal opportunity to study the geomorphic response of a meandering, gravel-bed river to a catastrophic flood. The research effort has been simplified because of the unique field setting and because there were few modifications of the flood deposits or channel prior to the 1983 snowmelt season. The changes observed during the past 4 years can, therefore, be related to a well- defined baseline. The results of this work can be formulated in terms of the magnitude and frequency of geomorphic processes (Wolman and Miller, 1960; Baker, 1977) and in terms of the concept of landform recovery from extreme events (Wolman and Gerson, 1978). The field site is also being used to study sediment transport at a detailed scale because, in gravel-bed rivers, there is a limited understanding of many processes (Hey, et al., 1981; Thorne, et al., in press).

Eighty channel cross sections have been established between the Fall River-Roaring River confluence and the downstream end of Horseshoe Park (Fig. 2); these have been surveyed annually. Selected cross sections have been used to monitor changes in bed material texture. Sediment load measurements have been made throughout the snowmelt periods at 4 sampling stations. The results of previous work are available in several published manuscripts and unpublished reports (Pitlick and Thorne, 1987; Pitlick, et al., 1987; Pitlick and Harvey, 1986; Pitlick, 1985). The information presented here is complimentary to earlier reports and describes (1) sediment transport data from 4 localities, (2) changes in the channel morphology of Fall River, (3) detailed studies of channel adjustment within the sediment storage zone in Horseshoe Park and (4) a summary of geomorphic adjustments of Fall River since 1983.

During the 1986 field season, sediment loads were monitored on Roaring River and Fall River. Repeated measurements of suspended load and bed load were made throughout the snowmelt period at 4 localities (Fig. 2): the footbridge across the Roaring River alluvial fan, the site immediately upstream of the U.S. Hwy. 34 bridge (Stanley), a site in the middle of the storage zone (Cross Section 57), and a site at the downstream end of Horseshoe Park (Ethel). All cross sections established between the Roaring River-Fall River confluence and the downstream end of Horseshoe Park were resurveyed in 1986.

In previous reports, the development and persistence of a large sediment storage zone in the downstream portion of Horseshoe Park (Fig. 2) was described (Pitlick and Thorne, 1987; Pitlick, 1985). Detailed studies of the lower 400 m of this reach of Fall River were initiated in 1985 and were continued in 1986. Repeated sediment load measurements were made at cross section 57, in the middle of the study reach. Channel adjustments were determined from repeated cross section surveys, and from 4 topographic surveys of the full study reach using an electronic distance meter-theodolite. The purpose of these surveys was to develop detailed maps showing the adjustment of bed topography to changing flow and sediment transport conditions.

The 4-year Fall River data set represents a unique study of a catastrophically-effected stream. The results of this work provide important insight into the short- term rates and mechanisms of geomorphic response following large flood events. A summary of the significant changes which have occurred on Fall River since 1983 is presented in the final section of this report.

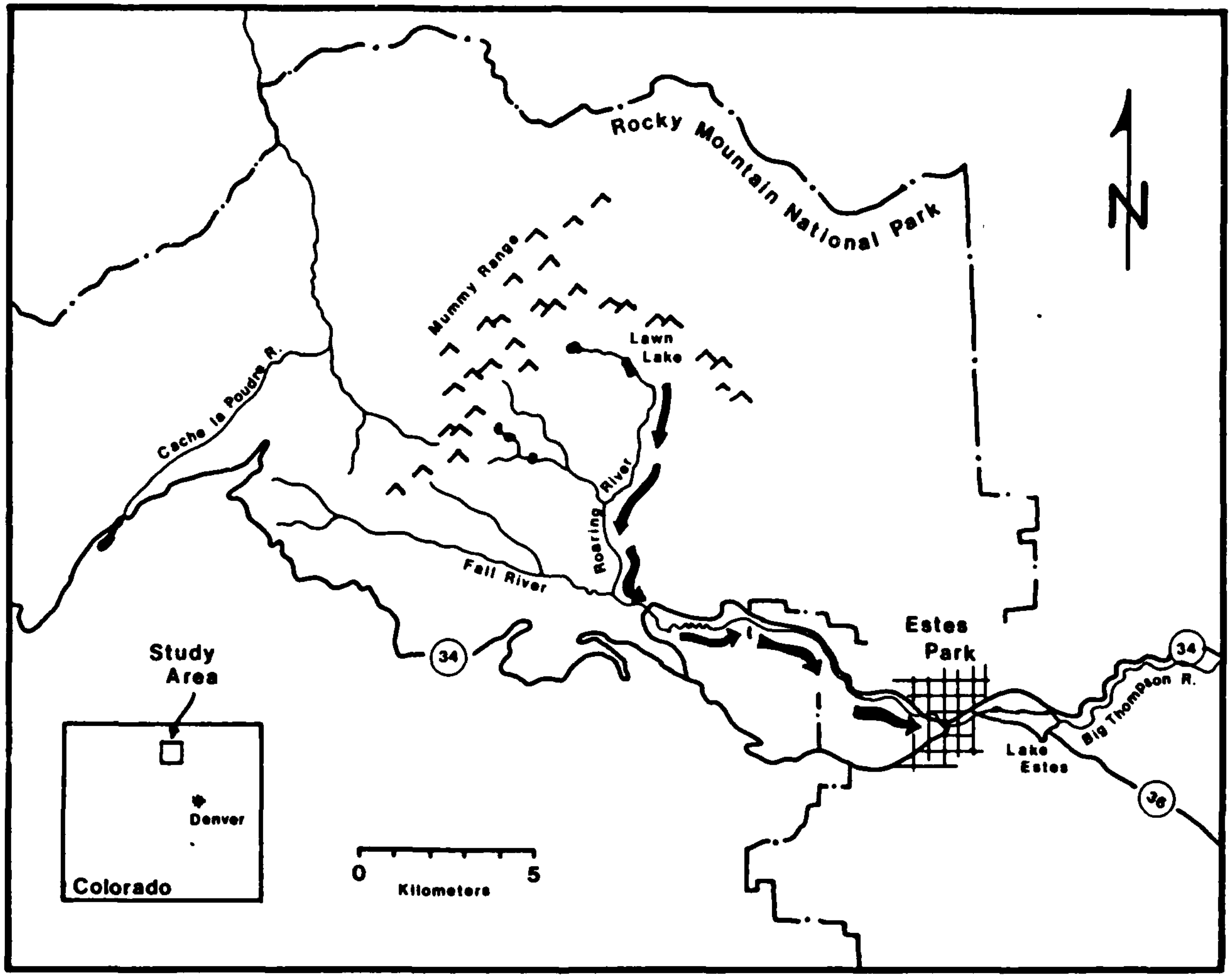


Figure 1. Location map of the Roaring River and Fall River drainages. Dark arrows indicate the course of the Lawn Lake flood

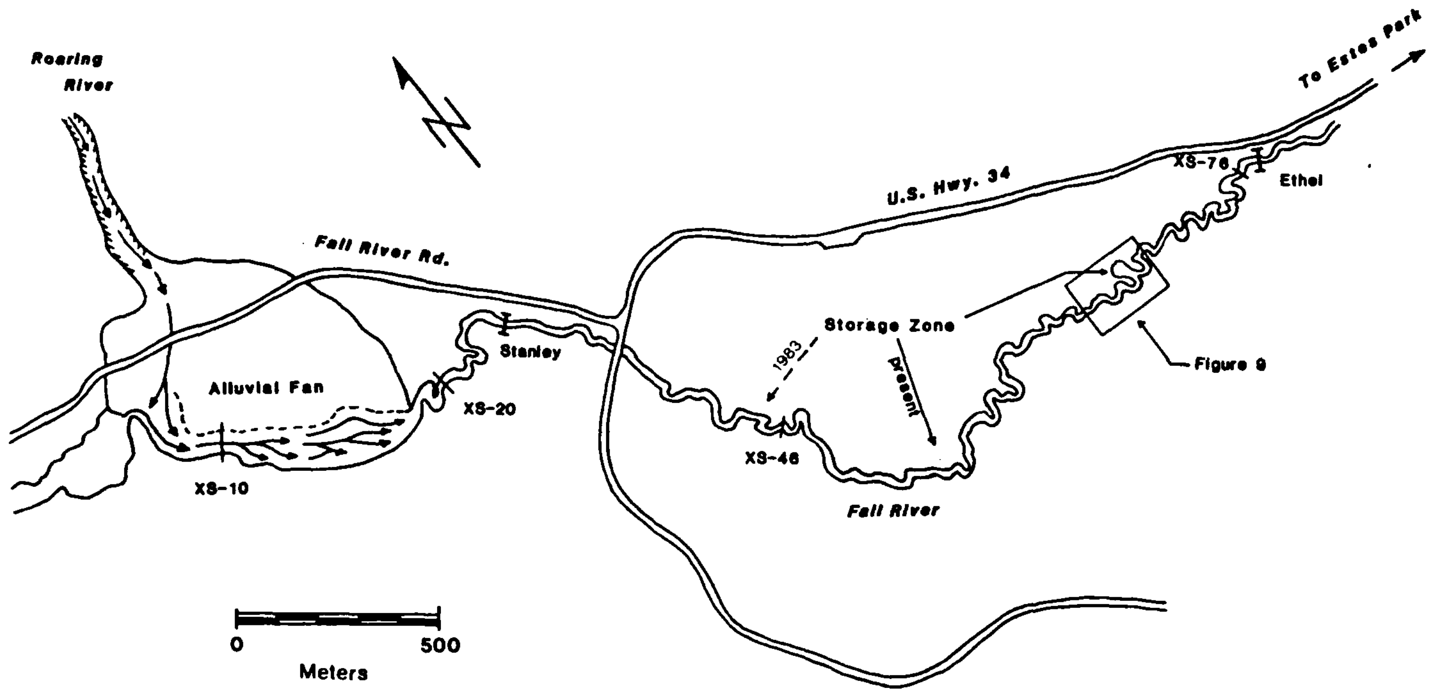


Figure 2. Map of Horseshoe Park study area showing the locations of selected cross sections, sediment load measurement sites and the sediment storage zone.

Setting

Roaring River and Fall River drain mountainous terrain within Rocky Mountain National Park. Their drainage basins are underlain by Precambrian crystalline rocks mantled by glacial deposits. These basins receive approximately 700 mm of precipitation annually, most of which falls as snow between October and May at elevations above 2,500 m. Vegetation is sparse above 3,000 m with large areas of scree, bare rock and tundra; lower elevations have a dense coniferous forest cover and weakly developed soils.

Roaring River, a boulder bedded stream draining 33 Km^2, flows from Lawn Lake for 7.25 Km down a steep valley (avg. slope = 0.10 m/m) to its confluence with Fall River in Horseshoe Park (Fig.1). Fall River flows through Horseshoe Park at an average gradient of 0.0015 m/m. Horseshoe Park, which takes its name from the tortuous meander bends of Fall River, was a lake during the most recent Pleistocene glacial phase. Prominent Pinedale-age (Richmond, 1960) terminal moraines define the lower limit of Horseshoe Park. Fall River has a drainage area of 90 Km^2 at this point.

The Lawn Lake flood was generated by the catastrophic failure of an 80-year-old earthfill dam on July 15, 1982. Within six hours, over 830,000 m^3 of water were released from Lawn Lake to the valleys of Roaring River and Fall River. The instantaneous peak discharge from Lawn Lake to the Roaring River was approximately 500 m^3/s, 30-times larger than the estimated discharge of the 500-year flood (Jarrett and Costa, 1985). The flood incised deeply into the glacial deposits that mantle much of the Roaring River valley floor, and, in the steeper reaches, scoured the channel to bedrock. Much of the material eroded by the flood was deposited within Roaring River as a series of discontinuous alluviated reaches and alluvial fans, the most spectacular of which is the Roaring River fan (Fig. 2).

The flood peak attenuated to 200 m^3/sec through Horseshoe Park (Jarrett and Costa, 1985) because of the reduction in valley gradient and the increase in floodplain width. The flood had little effect on Fall River downstream of the Roaring River fan and within Horseshoe Park, because it was of short duration, much of the flow was dispersed over the valley floor, and the pre-flood channel was extremely stable and had a low gradient. At the lower end of Horseshoe Park, Cascade dam, a small concrete structure, ponded the flood temporarily. Eventually, this dam also failed, increasing the flood peak to 450 m^3/sec (Jarrett and Costa, 1985) and causing severe channel erosion downstream. The flood then entered the town of Estes Park, causing an estimated $36 million in damage. Further downstream damage and loss of life were prevented when the flood reached Lake Estes, a large reservoir operated by the U.S. Bureau of Reclamation.

HYDROLOGY

The continuous recording stream gage in Horseshoe Park provided a discharge record for the 1986 snowmelt season. The 1986 snowmelt began in early-June and was a period of above average runoff (Fig. 3). Peak discharges were recorded between June 6-9 and between June 17-21, 1986. The instantaneous maximum discharge, recorded on June 19, was 8.5 m^3/s and ranks as the 20^{th} highest discharge for the 40-year synthetic record constructed for Fall River in Horseshoe Park (see Pitlick, 1985). Recessional snowmelt flows were moderately high through late June and early July. Thunderstorm-generated flows were only slightly higher than snowmelt base flows. Although peak discharges were not as high as in previous years, moderately high flows were sustained for longer periods than in any year since 1983 (Table 1). The mean annual flood was exceeded for 10 days, corresponding to the two peak snowmelt periods mentioned above. Mean daily flows for Fall River in Horseshoe Park for the period May1-August 31, 1986 are given in Table 2.

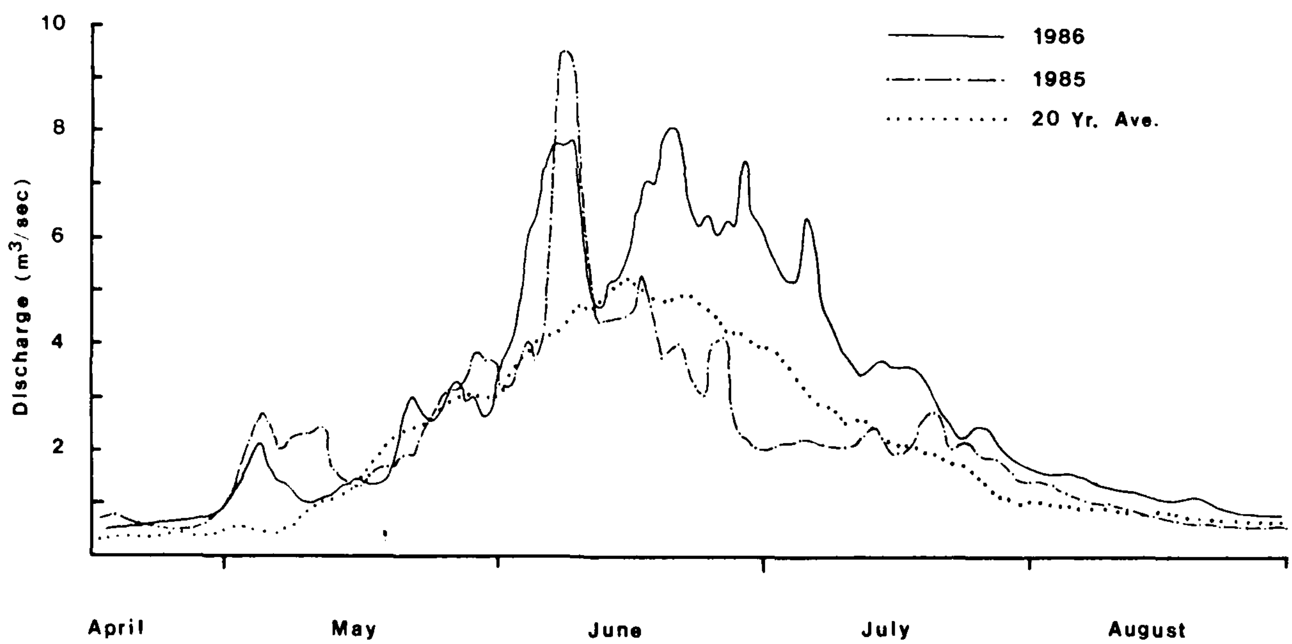


Figure 3. Hydrographs for Fall River in Horseshoe Park for 1986, 1985 and 20-year average.

TABLE 1. Flood Frequency Data for Fall River, Horseshoe Park

Return Period, T (years)	Exceedence Probability, P (P=1/T)	Discharge (M^3/sec)	Number of days flow equaled or exceeded 1983	1984	1985	1986
1.50	0.67	6.31	26	2	4	18
2.22(1)	0.45	7.46	20	1	3	10
5.0	0.20	9.94	10	-	-	-
10	0.10	10.79	-	-	-	-
20	0.05	11.87	-	-	-	-

(1) Mean Annual Flood

TABLE 2. Mean Daily Discharges, 1986 (M^3/sec)

Day	May	June	July	August
1	0.99	3.64	5.72	1.54
2	1.27	4.07	5.44	1.54
3	1.60	4.83	5.19	1.59
4	1.91	6.22	5.23	1.54
5	2.20	6.44	6.44	1.52
6	1.70	7.47	5.84	1.37
7	1.41	7.80	4.68	1.35
8	1.36	7.74	4.33	1.35
9	1.14	7.88	3.85	1.52
10	1.01	6.64	3.67	1.47
11	0.98	4.83	3.38	1.31
12	1.08	4.63	3.52	1.29
13	1.10	5.22	3.72	1.38
14	1.31	5.23	3.72	1.32
15	1.31	5.59	3.59	1.19
16	1.49	6.51	3.61	1.09
17	1.36	7.15	3.59	1.06
18	1.36	7.04	3.49	1.06
19	1.45	7.98	3.16	1.60
20	1.84	8.13	2.69	1.14
21	2.58	7.63	2.54	1.29
22	3.07	6.69	2.22	1.34
23	2.71	6.19	2.23	1.25
24	2.54	6.51	2.48	1.17
25	2.69	6.04	2.48	1.09
26	3.18	6.41	2.19	1.14
27	3.32	6.24	1.99	1.03
28	2.90	7.50	1.84	0.94
29	3.06	6.44	1.72	0.94
30	2.62	6.24	1.64	1.09
31	2.86	-	1.59	1.08

SEDIMENT TRANSPORT

Measurements of sediment load were made at 1 sampling station on Roaring River and 3 sampling stations on Fall River (Fig. 2). The Roaring River station was previously manned by members of the British Institute of Hydrology; the sampling stations on Fall River have been maintained as part of the present study. The periods of record for each of the Fall River stations (Stanley, Ethel, and Cross Section 57) are respectively, 4 years, 3 years, and 2 years. The 1986 sediment transport data for each of these stations are summarized in Tables 3 to 6.

Table 3. Hydraulic and Sediment Transport Data, Roaring River, 1986

Date	Time	Discharge (M^3/sec)	Bed load Transport Rate (Kg/M/s)	Median Grain Size (mm)	Sediment Sorting
6-2	1500	1.50	0.0020	2.60	1.87
6-3	1405	1.96	0.0031	1.70	2.38
6-4	1055	2.34	0.0190	2.00	2.16
6-5	1545	2.30	0.0180	1.60	1.97
6-6	1415	2.65	0.0300	1.40	1.59
6-7	1710	3.18	0.0380	1.30	1.30
6-9	1530	2.92	0.0170	1.70	1.90
6-11	1235	1.73	0.0010	1.00	1.04
6-12	1750	1.85	0.0050	1.40	1.35
6-14	1150	1.93	0.0008	1.70	1.65
6-16	1525	2.42	0.0070	1.50	1.36
6-17	1340	2.53	0.0060	1.30	1.23
6-19	1030	2.77	0.0100	1.30	1.28
6-20	1700	2.88	0.0190	1.70	1.44
6-22	1645	2.42	0.0050	2.20	2.04
6-23	1850	2.42	0.0050	1.20	1.80
6-25	1450	2.22	0.0020	1.10	1.23
6-27	1420	2.34	0.0020	1.20	1.13
6-30	1450	2.24	0.0020	1.50	1.48
7-3	1520	1.91	0.0008	1.10	1.28
7-7	1400	1.73	0.0003	1.20	1.41
7-9	1200	1.49	0.0002	0.96	1.35
7-11	1110	1.30	0.0002	0.90	1.52

Table 4. Hydraulic and Sediment Transport Data, Stanley, 1986

Date	Time	Discharge (M^3/sec)	Velocity (M/sec)	Depth (M)	Friction Factor	Unit Stream Power (Kg/M/s)	Bed load Transport Rate (Kg/M/s)	Median Grain Size (mm)	Sediment Sorting
5-23	1100	2.00	0.60	0.39	0.28	7.38	0.020	0.94	1.29
5-24	1100	1.83	0.53	0.40	0.35	6.74	0.017	0.96	1.11
5-25	1115	1.89	0.56	0.40	0.33	7.00	0.019	0.74	1.23
5-27	920	2.79	0.71	0.47	0.23	10.48	0.027	0.94	1.28
5-28	900	2.24	0.63	0.42	0.27	8.31	0.021	1.20	1.20
5-29	1600	2.24	0.62	0.42	0.27	8.26	0.026	1.10	1.23
5-31	1630	2.24	0.62	0.42	0.28	8.26	0.014	1.00	1.05
6-2	1130	3.37	0.80	0.50	0.20	12.44	0.031	1.50	1.42
6-3	1500	4.40	0.90	0.58	0.18	16.23	0.011	1.20	1.80
6-3	2235	6.28	1.04	0.71	0.17	23.20	0.032	2.30	1.82
6-4	1135	5.25	0.96	0.64	0.17	19.40	0.014	1.10	1.53
6-5	1625	5.15	0.94	0.64	0.18	19.02	0.017	1.10	1.33
6-6	1455	5.94	1.01	0.69	0.17	21.93	0.020	1.40	1.56
6-6	2315	7.38	1.15	0.76	0.14	27.24	0.078	3.20	1.80
6-7	2310	7.14	1.13	0.74	0.15	26.36	0.083	1.80	1.79
6-9	1405	6.55	1.11	0.69	0.14	24.21	0.102	2.00	1.47
6-11	1145	3.88	0.86	0.53	0.18	14.34	0.084	1.10	1.10
6-12	1655	4.16	0.89	0.55	0.18	15.35	0.069	1.10	1.46
6-13	1700	4.50	0.93	0.57	0.16	16.61	0.055	2.40	1.84
6-14	1145	4.33	0.90	0.57	0.18	15.98	0.038	1.60	1.25
6-16	1610	5.42	0.97	0.66	0.18	20.03	0.047	2.20	1.58
6-17	1445	5.66	1.00	0.67	0.17	20.92	0.030	1.50	1.62
6-19	1130	6.21	1.04	0.70	0.16	22.94	0.004	0.64	1.63
6-20	1700	6.45	1.02	0.75	0.18	23.83	0.036	4.00	1.86
6-20	2330	7.31	1.10	0.78	0.16	26.99	0.035	2.40	1.88
6-22	1550	5.42	0.96	0.67	0.18	20.03	0.045	1.80	1.37
6-23	1625	5.42	0.99	0.65	0.17	20.03	0.052	1.60	1.36
6-24	1720	5.60	0.97	0.68	0.18	20.66	0.041	1.30	1.25
6-25	1445	4.98	0.93	0.63	0.18	18.39	0.047	1.80	1.28
6-27	1530	5.25	1.00	0.62	0.15	19.40	0.047	0.80	1.15
6-29	1430	5.25	0.97	0.63	0.17	19.40	0.017	2.00	1.36
6-30	1400	5.01	0.93	0.63	0.18	18.51	0.010	1.20	1.12
7-2	1655	4.67	0.91	0.60	0.18	17.25	0.038	-	-
7-3	1500	4.29	0.86	0.59	0.20	15.85	0.020	1.20	1.23
7-7	1345	3.88	0.79	0.58	0.23	14.34	0.005	0.90	1.04
7-9	1130	3.33	0.77	0.51	0.22	12.31	0.024	1.10	1.03
7-11	1145	2.92	0.69	0.50	0.26	10.79	0.012	0.95	1.04
7-14	1250	3.03	0.70	0.51	0.27	11.17	0.003	0.54	0.59
7-18	1000	2.85	0.64	0.52	0.32	10.54	0.009	0.74	0.95
7-28	1630	1.35	0.37	0.43	0.77	4.97	0.001	0.55	0.85

Note: Water surface slope was 0.0032 m/m and channel width was 9.0 m for all samples.

Table 5. Hydraulic and Sediment Transport Data, Cross Section 57, 1986

Date	Discharge (M^3/sec)	Velocity (M/sec)	Depth (M)	Slope	Friction Factor	Unit Stream Power (Kg/M/s)	Bed load Transport Rate (Kg/M/s)	Median Grain Size (mm)	Sediment Sorting
6-3	3.79	0.68	0.46	0.00225	0.175	6.97	0.139	0.85	1.44
6-5	4.45	0.72	0.51	0.00230	0.179	8.23	0.175	0.92	1.10
6-6	4.67	0.69	0.56	0.00235	0.217	8.82	0.162	0.85	1.14
6-8	4.83	0.70	0.57	0.00240	0.217	9.48	0.182	1.00	1.30
6-11	3.27	0.62	0.44	0.00245	0.217	6.55	0.143	0.85	1.08
6-12	3.01	0.61	0.41	0.00250	0.218	6.05	0.107	1.00	1.35
6-14	3.78	0.68	0.46	0.00220	0.170	6.80	0.115	1.30	1.34
6-16	4.43	0.68	0.53	0.00180	0.162	6.41	0.120	1.00	1.24
6-17	3.68	0.61	0.49	0.00150	0.155	4.44	0.113	0.95	1.29
6-19	4.48	0.74	0.50	0.00150	0.107	5.40	0.129	0.92	1.17
6-20	4.01	0.69	0.48	0.00150	0.120	4.84	0.118	0.95	1.16
6-22	3.93	0.69	0.47	0.00150	0.115	4.82	0.092	0.95	1.12
6-23	3.50	0.64	0.46	0.00150	0.131	4.33	0.078	0.86	1.22
6-24	3.35	0.64	0.44	0.00150	0.126	4.14	0.093	1.10	1.42
6-25	3.34	0.68	0.41	0.00150	0.105	4.09	0.075	1.10	1.39
6-27	3.09	0.67	0.38	0.00150	0.100	3.73	0.087	0.92	1.31
6-30	3.09	0.69	0.37	0.00160	0.099	3.98	0.112	0.95	1.19
7-1	2.97	0.68	0.37	0.00167	0.105	4.05	0.083	1.10	1.30
7-2	2.64	0.64	0.34	0.00167	0.109	3.55	0.110	0.82	1.28
7-3	2.82	0.66	0.36	0.00170	0.110	3.91	0.113	0.78	1.09
7-7	2.40	0.59	0.33	0.00175	0.131	3.38	0.091	0.80	1.15
7-9	2.63	0.66	0.33	0.00190	0.115	4.08	0.103	-	-
7-11	2.29	0.66	0.29	0.00200	0.105	3.75	0.086	-	-
7-12	2.34	0.71	0.27	0.00200	0.085	3.83	0.129	0.95	1.31
7-14	2.63	0.70	0.31	0.00200	0.100	4.29	0.090	0.95	1.14
7-16	2.40	0.71	0.32	0.00200	0.102	4.48	0.059	0.95	1.36
7-18	2.41	0.66	0.31	0.00200	0.110	3.95	0.144	0.75	1.04
7-21	2.12	0.65	0.33	0.00200	0.123	4.16	0.098	0.86	1.11
7-26	2.01	0.64	0.32	0.00200	0.125	4.07	0.064	0.68	0.90
7-28	1.98	0.64	0.33	0.00200	0.125	4.10	0.103	-	-

Table 6. Hydraulic and Sediment Transport Data, Ethel, 1986

Date	Time	Discharge (M^3/sec)	Velocity (M/sec)	Depth (M)	Friction Factor	Unit Stream Power (Kg/M/s)	Bed load Transport Rate (Kg/M/s)	Median Grain Size (mm)	Sediment Sorting
5-23	1320	2.41	-	-	-	-	0.116	0.80	1.06
5-24	1300	2.21	0.59	0.53	0.17	4.34	0.087	0.80	1.11
5-25	1215	2.29	0.63	0.52	0.14	4.49	0.081	0.80	0.96
5-26	1715	3.18	0.71	0.64	0.14	6.24	0.014	0.80	1.08
5-27	1730	2.91	0.71	0.63	0.14	6.14	0.106	0.90	1.06
5-28	1440	2.60	0.70	0.53	0.12	5.10	0.089	0.85	0.99
5-29	1700	2.68	0.68	0.56	0.13	5.25	0.170	0.85	1.00
5-30	1730	2.29	0.63	0.52	0.14	4.49	0.087	0.90	0.96
6-2	1245	3.96	0.80	0.71	0.12	7.76	0.205	0.90	1.18
6-3	1625	5.32	0.92	0.82	0.11	10.43	0.276	0.90	1.04
6-4	0005	7.33	0.95	1.10	0.13	14.39	0.390	0.92	1.18
6-5	2320	7.45	1.01	1.06	0.12	14.62	0.614	1.00	1.10
6-6	1720	6.09	0.81	1.07	0.18	11.95	0.200	0.90	1.19
6-7	0015	8.42	0.96	1.25	0.15	16.52	0.611	0.88	0.92
6-8	0010	8.11	0.93	1.25	0.16	15.91	0.385	1.50	1.12
6-9	1610	7.49	0.93	1.15	0.15	14.69	0.324	1.70	1.30
6-11	1320	4.54	0.87	0.75	0.11	8.91	0.228	0.95	0.99
6-12	1820	5.32	0.91	0.83	0.11	10.43	0.148	0.80	1.06
6-13	1700	5.24	0.93	0.81	0.10	10.28	0.187	0.95	1.06
6-14	1005	5.16	0.83	0.89	0.14	10.12	0.225	1.00	1.16
6-16	1440	5.86	0.88	0.95	0.14	11.49	0.242	0.76	0.93
6-17	1550	6.75	0.93	1.04	0.13	13.25	0.221	0.80	1.13
6-19	1550	7.64	0.99	1.10	0.12	15.00	0.343	1.00	0.99
6-20	1530	7.33	0.95	1.10	0.13	14.39	0.258	1.40	1.27
6-20	2330	8.42	0.96	1.25	0.15	16.52	0.496	1.00	1.08
6-21	1035	7.18	0.95	1.08	0.13	14.08	0.279	1.10	1.20
6-22	1435	6.29	0.89	1.00	0.14	12.33	0.185	0.80	1.11
6-23	1800	6.48	0.99	0.93	0.10	12.71	0.287	0.96	1.28
6-24	1600	6.29	0.93	0.97	0.12	12.33	0.405	0.88	1.10
6-25	1345	5.78	0.90	0.91	0.12	11.34	0.317	1.20	1.22
6-29	1505	6.09	0.91	0.96	0.13	11.95	0.364	1.20	1.24
6-30	1330	5.78	0.88	0.94	0.13	11.34	0.255	1.10	1.05
7-1	1130	5.51	0.87	0.91	0.13	10.81	0.218	1.00	1.25
7-3	1420	5.08	0.83	0.88	0.14	9.97	0.134	0.96	1.23
7-7	1050	4.69	0.84	0.80	0.13	9.21	0.176	1.00	1.20
7-9	1045	3.96	0.76	0.74	0.14	7.76	0.117	-	-
7-11	1230	3.45	0.66	0.75	0.19	6.80	0.125	0.66	1.07
7-14	1215	3.57	0.75	0.68	0.13	7.00	0.184	0.92	1.20
7-21	1415	2.68	0.68	0.56	0.13	5.25	0.129	0.70	0.93
7-28	1840	1.67	0.49	0.48	0.22	3.27	0.081	-	-

Note: Water surface slope was 0.0014 m/m and channel width was 7.0 m for all samples

Bed load transport rates in 1986 were, on the average, lower at both the Roaring River station and at Stanley than in previous years. The average of 23 bed load measurements on Roaring River in 1986 was 0.008 Kg/m/sec and the majority of measurements fell within a range of 10^{-2} to 10^{-3} kg/m/sec. The average of 40 bed load measurements at Stanley in 1986 was 0.033 kg/m/sec and the majority of transport rates fell within a range of 10^{-1} to10^{-2} kg/m/sec. As discussed previously, snowmelt discharges were not exceptionally high in 1986. The lack of very high flows is partly responsible for the lower sediment yields from Roaring River and the alluvial fan. In addition, these areas are becoming increasingly stable and anything less than exceptionally high discharges or a large landslide from one of the Roaring River gulley walls will not likely produce the high sediment loads observed in 1983.

Bed load transport rates in 1986 were, on the average, about the same at both Cross Sectior 57 and at Ethel as in previous years. The average of 30 bed load measurements at Cross Section 57 was 0.11 kg/m/sec and most observations fell within a narrow range of this value. The average of 40 bed load measurements at Ethel was 0.25 kg/m/sec and the majority of transport rates fell within a range of 0.5 to 0.05 kg/m/sec. The maintenance of high transport rates at both of these stations reflects the continued output of sediment from the storage zone which first formed in 1983. In the near future, the storage zone will continue to be the principal source for sediment leaving Rocky Mountain National Park.

Bed load transport at each of the sampling stations followed the trend of the 1986 snowmelt hydrograph (Fig. 4). In all cases, the initial snowmelt peak between June 6-9 produced the highest bed load transport rates. Similar trends have been noted previously (Pitlick and Harvey, 1986), and reflect the initial flush of sediment deposited during the waning stage of the previous year's snowmelt as well as the efflux of sediment deposited in the channel by bank collapse and wind erosion during the winter months. The subsequent snowmelt peak between June 17-21 produced lower transport rates than the early-June peak because much of the easily-moved sediment was exhausted from within the channel.

A second point illustrated in Figure 4 is the difference in bed load transport rates at each of the sampling stations. Note that, for illustrative purposes, bed load transport was not plotted at the same scale for each station. This is because sediment loads measured on Roaring River were an order of magnitude lower than those measured at Stanley which, in turn, were an order of magnitude lower than those measured at Cross Section 57 or Ethel. Thus, within the 5-Km length of stream between Roaring River and the downstream end of Horseshoe Park, there is approximately a 100-fold increase in sediment load. Although the gradient of Fall River decreases by a factor of 10 over this length and the upstream reaches were the most highly disturbed by the Lawn Lake flood, the downstream increase in sediment load is primarily the result of a downstream increase in the present activity of sediment sources. Roaring River and the upper reaches of Fall River are becoming increasingly stable, and flows that are competent to move the boulder and coarse gravel bed material do not occur more than a few days per year. Sand and fine gravel-sized sediment, which are mobile at flows which occur many days of the year, have been exhausted from the upper reaches but become increasingly available in the downstream reaches of Horseshoe Park. As a result, high sediment loads are maintained for longer periods in the downstream reaches of Fall River than in the upstream reaches.

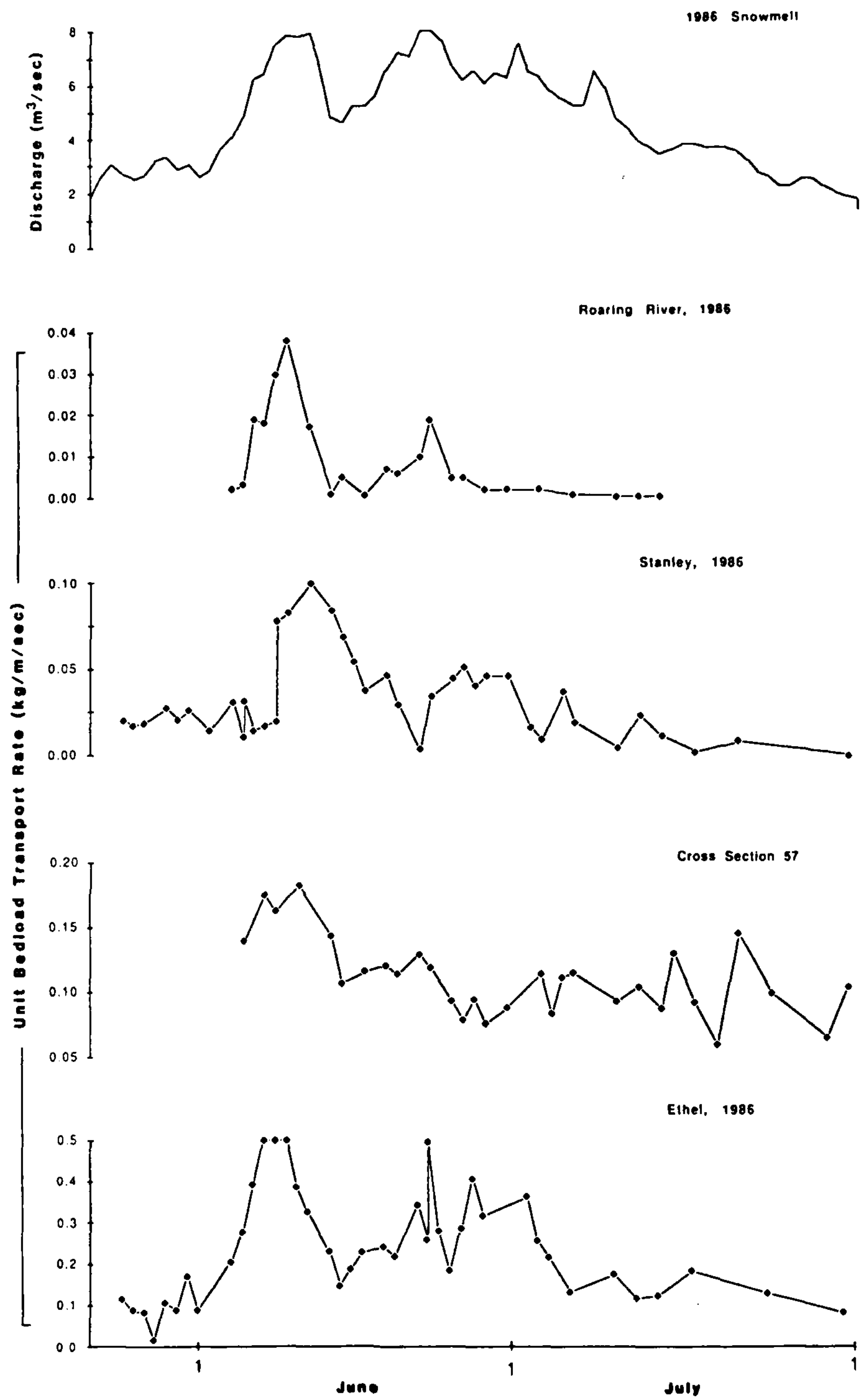


Figure 4. Comparison between water and bed load discharge at each sediment sampling site. Note that bed load transport rates are plotted at different scales for each station reflecting the order-of-magnitude increase in sediment loads from the upstream to the downstream stations.

Sediment rating curves, which relate unit bed load transport rate to unit stream power (the product of shear stress and velocity), have been revised for the 3 Fall River stations (Fig. 5). All rating curves show a positive correlation between unit stream power and unit bed load transport rate but the data are widely scattered. For each of these stations, the least squares relations between unit bed load tansport rate (qs, kg/m/sec) and unit stream power (w, kg/m/sec) are:

Stanley: $q_s = 0.002\, w^{1.20}$ ($r^2 = 0.20$)

Cross Section 57: $q_s = 0.04\, w^{0.65}$ ($r^2 = 0.60$)

Ethel: $q_s = 0.02\, w^{1.0}$ ($r^2 = 0.42$)

The sediment rating curves for each of the Fall River stations also express the condition of *increasing sediment loads from upstream to downstream. For a given unit stream power,* these relations predict a greater rate of sediment transport at downstream stations than at upstream stations. This is unusual because for a given discharge, unit stream power is lower at the downstream stations than at the upstream station due to the downstream decrease in slope. What the rating curve relationships show is that less of the available stream power is used to transport sediment at the upstream station than at the downstream stations and, as suggested above, this is primarily a function of the duration of flows competent to move the majority of the available sediment.

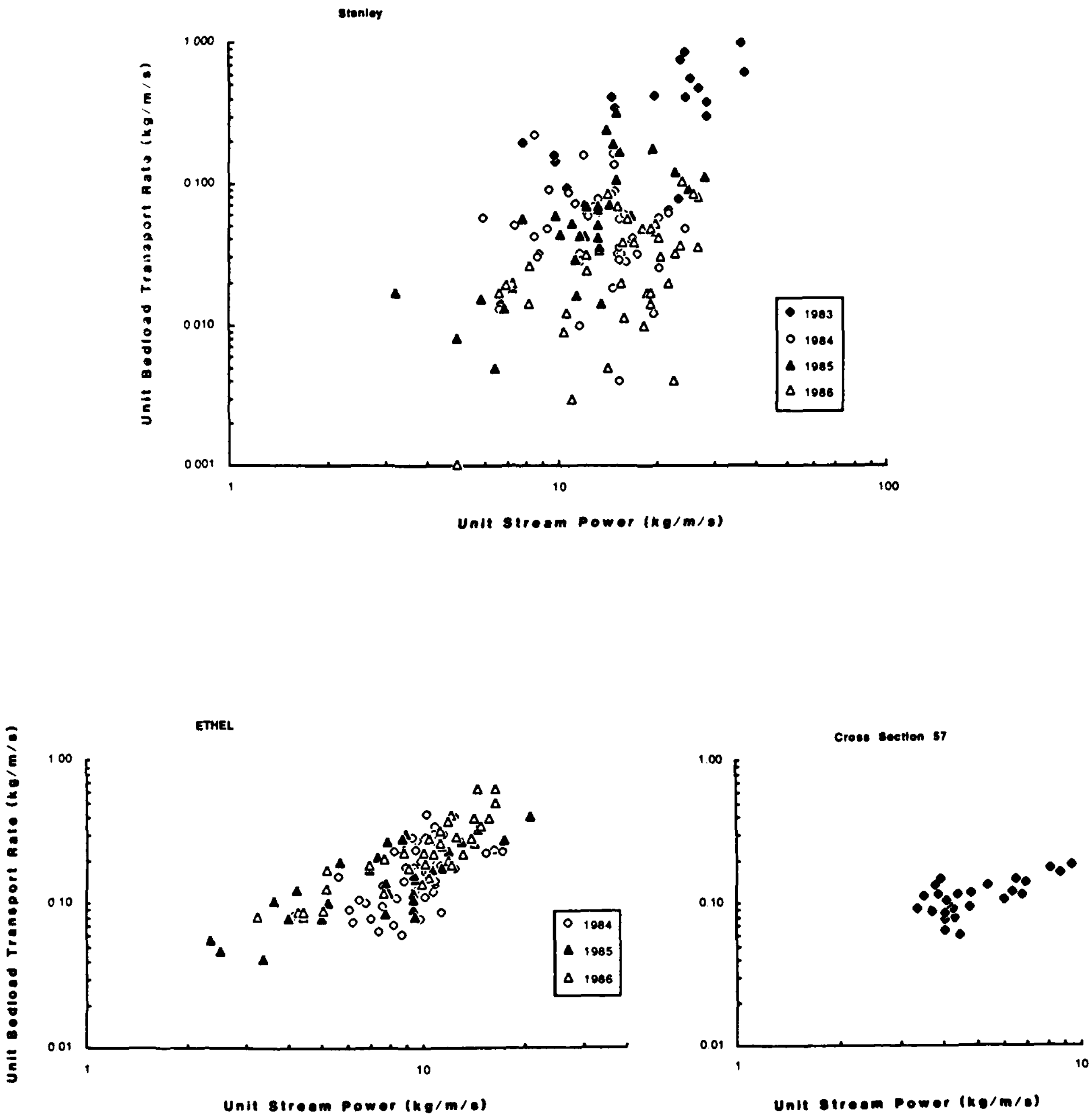


Figure 5. Sediment rating curves for the 3 Fall River sediment sampling sites.

CHANNEL MORPHOLOGY

All cross sections downstream of the Roaring River-Fall River confluence were resurveyed during the 1986 field season. With the exception of the sediment storage zone, channel changes in the Horseshoe Park reaches of Fall River were minor in 1986. The lack of significant channel changes during the 1986 snowmelt is a result of (1) declining sediment supply from Roaring River, (2) the presence of a coarse bed material armor within channels on the alluvial fan and, (3) the lack of persistent high flows.

Reach 1, the alluvial fan

Channels within the alluvial fan (Fig. 2) remain stable. The 1986 snowmelt flows were not sufficiently high nor was the sediment supply from Roaring River high enough to trigger major channel avulsions within the alluvial fan. As a result, there was little change in channel morphology at any of the cross sections within this reach of Fall River (Cross Sections 3 and 10, Fig. 6).

Reaches 2 and 3

Between the alluvial fan and the sediment storage zone (Fig.2), Fall River continues to maintain a single-thread, sinuous course. Channel cross sections within Reach 2 indicate only minor changes in bed elevation during the 1986 snowmelt runoff (Cross Sections 20 and 30, Fig. 7). The most notable channel changes in this reach were the result of slump-block failure of the outer banks (see cross section 30, Fig. 7). Outer bank erosion is a normal process in many meandering streams and there is no reason to believe that this process is being accelerated as a result of the Lawn Lake flood or subsequent events. The channel banks of Fall River are composed of a basal, unconsolidated gravel overlain by densly rooted silt and clay. Erosion of composite channel banks such as these, occurs by undercutting and removal of the basal gravel and subsequent slump-block failure of the overlying fine-grained sediments. Channel cross sections within Reach 3 show slight degradation of the bed (Cross Sections 46 and 53, Fig. 8) as the stream continues to excavate material deposited in 1983.

Reach 4, the sediment storage zone

As discussed previously (Pitlick and Thorne, 1987; Pitlick and Harvey, 1986; Pitlick, 1985), the high sediment loads of the 1983 snowmelt could not be conveyed through a 2000 meter-long reach of Fall River and a discrete sediment storage zone was formed. Within the upstream half of the storage zone, the channel has since degraded to the pre-1983 bed. Intuitively, it might have been expected that the storage zone would have moved downstream in wave-like fashion as sediment was eroded from the upper end and deposited at the lower end. However, this has not happened and two questions regarding the storage zone were the focus of studies in 1986: (1) why has the terminus remained in the same location and (2) how is the sediment eroded from the upstream part accomodated within the downstream part of the storage zone?

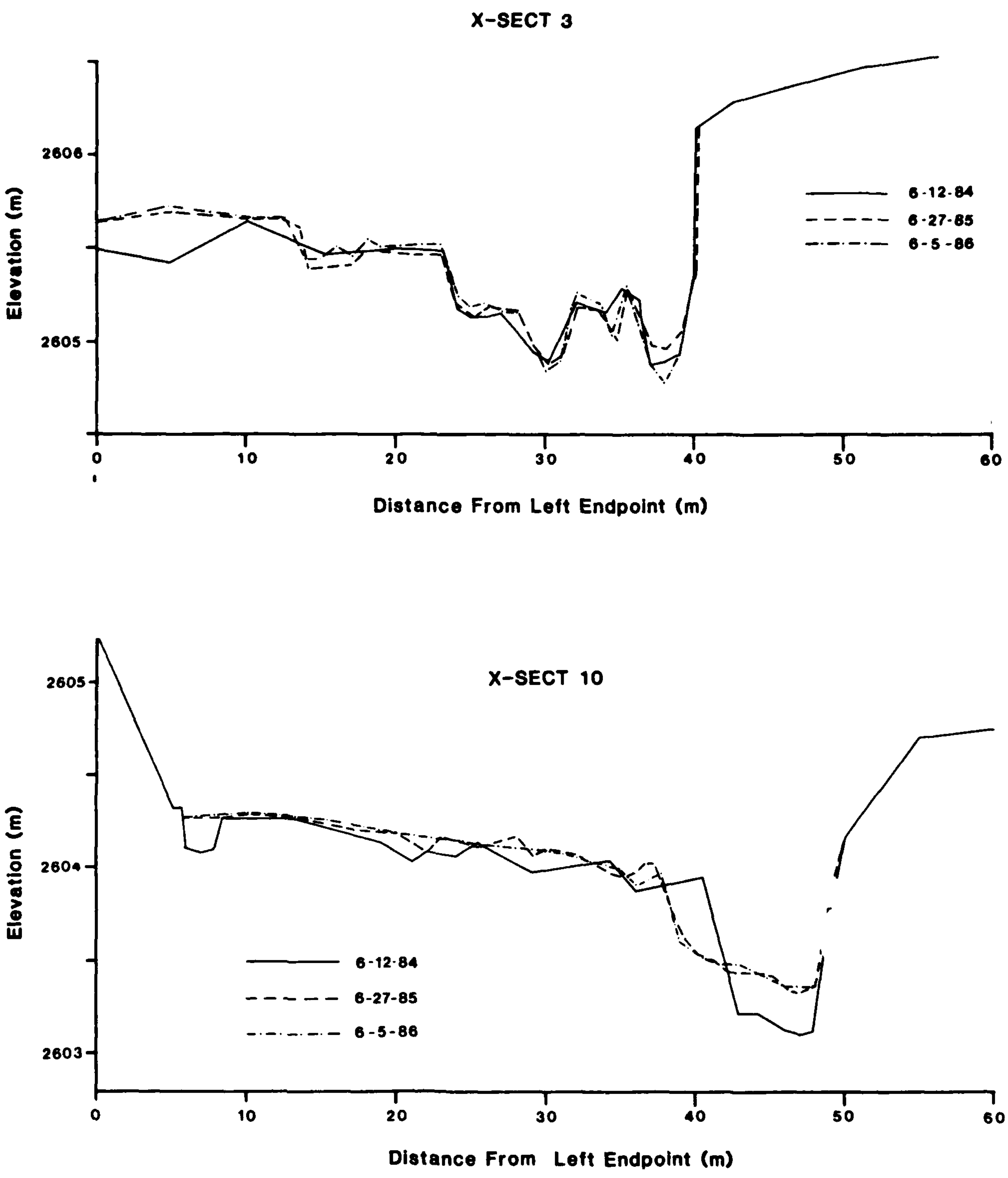
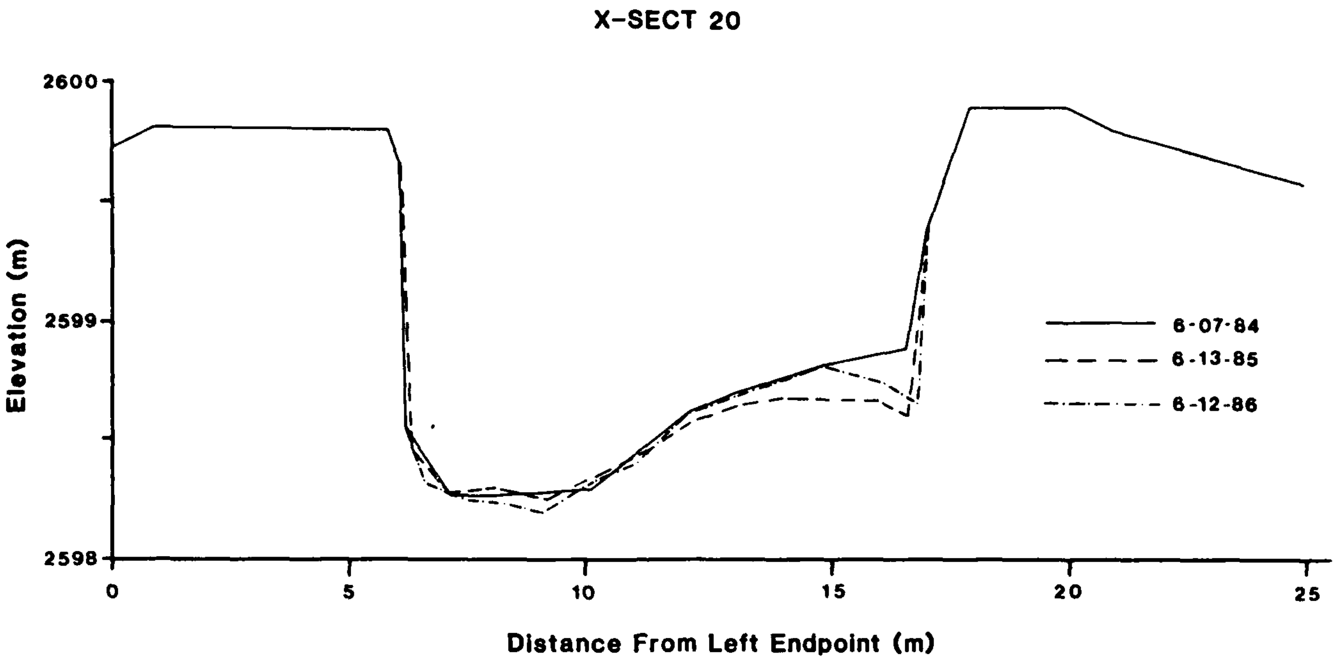


Figure 6. Channel cross sections on the alluvial fan.



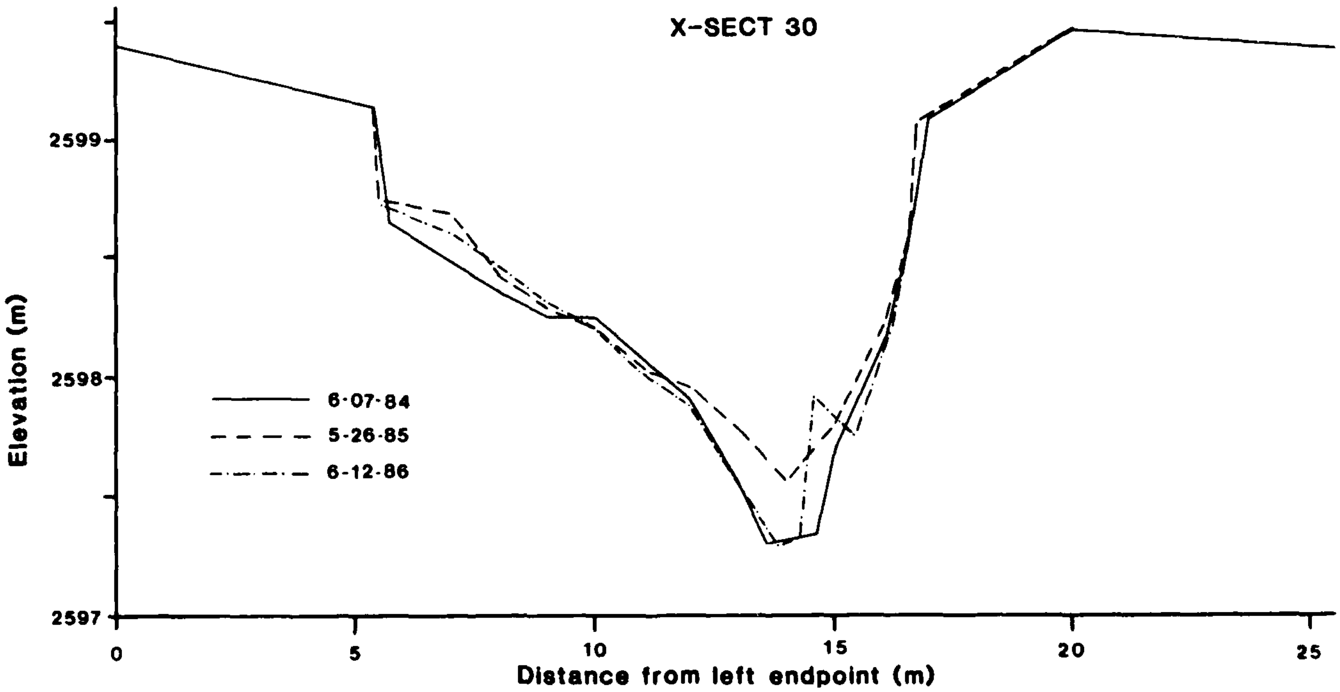
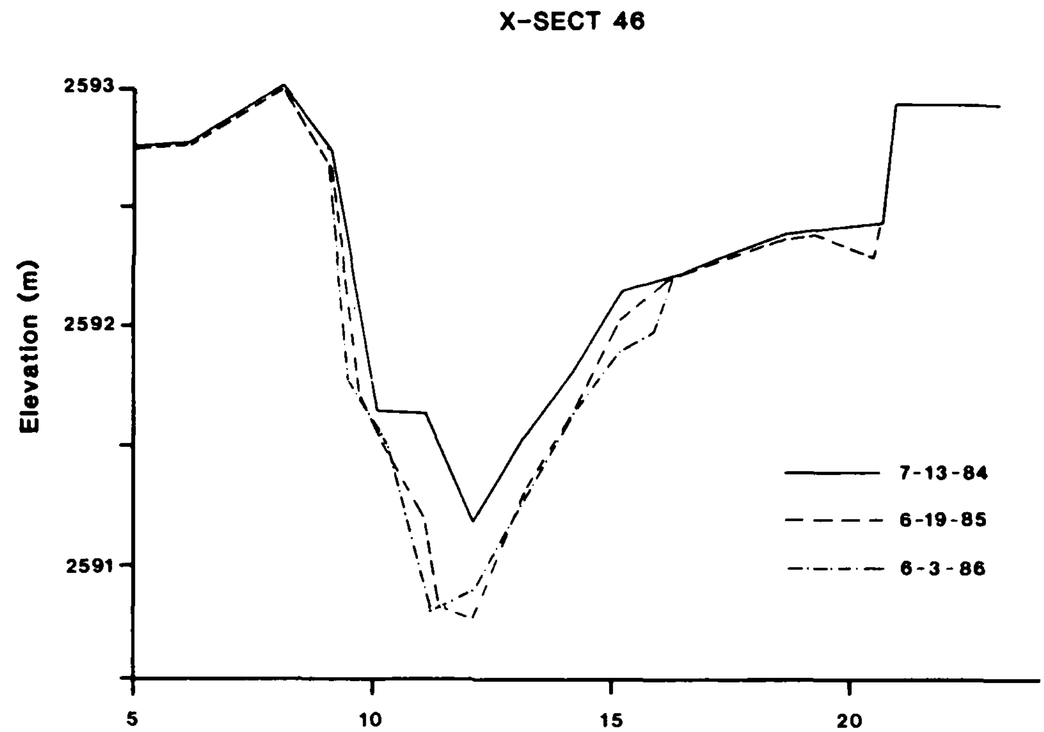


Figure 7. Channel cross sections within the reach immediately downstream of the alluvial fan.



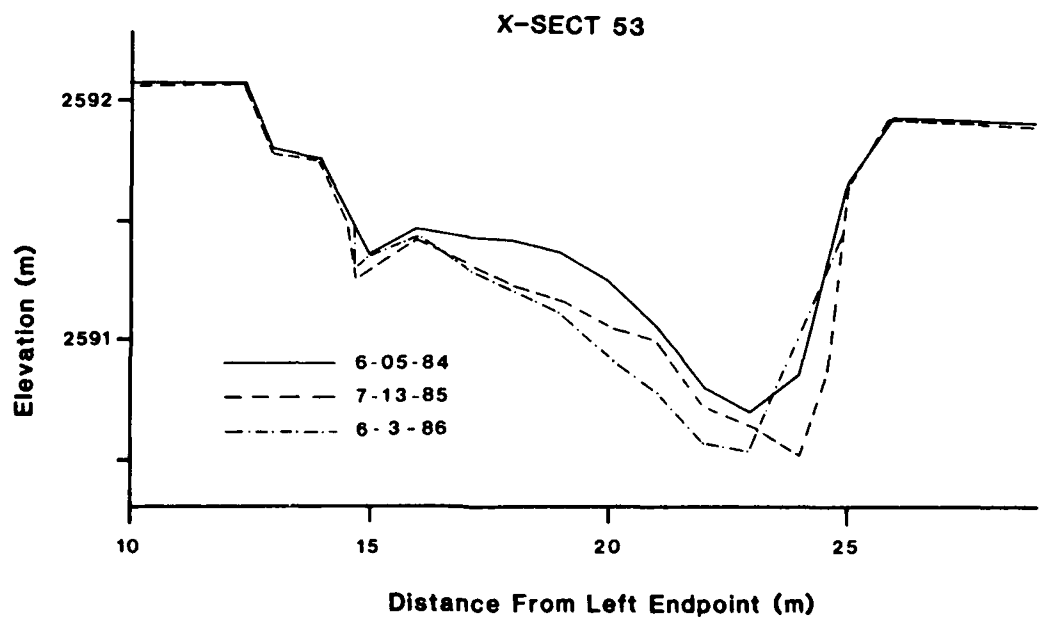


Figure 8. Channel cross sections downstream of the U.S. Highway 34 bridge.

Aerial photographs taken in late-September, 1983 revealed that the storage zone terminated at the downstream end of a single, very wide meander bend (Fig. 9). At this time, a small neck-cutoff had formed between this bend and the bend immediately downstream and a sediment plug had blocked flow through the cutoff meander (Fig. 9). The neck-cutoff has not enlarged significantly since 1983 and it is hypothesized that it has acted as a low-drop weir. At high discharges, flow through the cutoff is critical and this produces a scour hole both upstream and downstream of the neck. The maintenance of the scour hole promotes sediment transport and keeps sediment from migrating downstream as a "wave"; upstream of the scour hole, the flow is subcritical and for the same specific energy is deeper, thus promoting deposition.

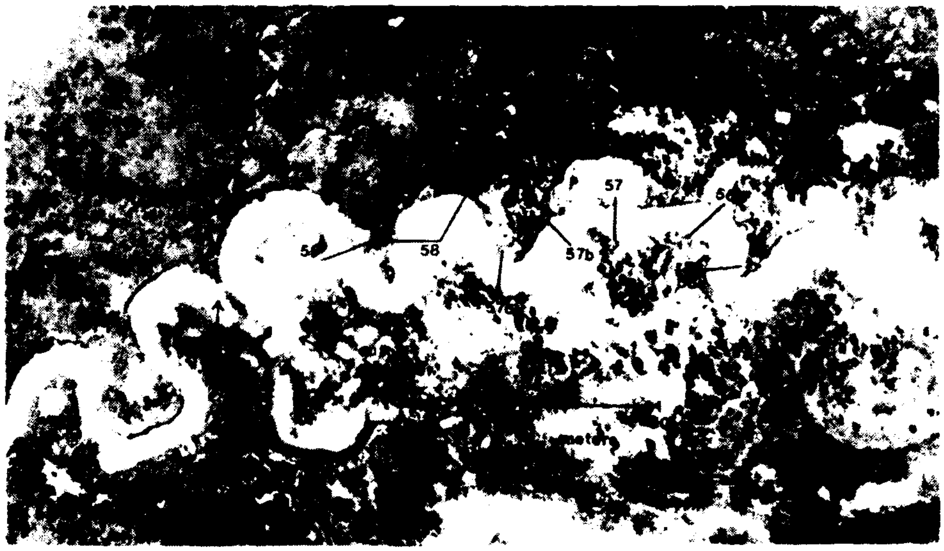


Figure 9. Aerial photograph showing the terminus of the storage zone at a neck-cutoff and the position of several channel cross sections referred to in text. Cross Section 57 was used as a sediment and discharge measurement station throughout the 1986 snowmelt runoff period.

Clearly, the hydraulic effect of the neck-cutoff would not extend very far upstream and a more general explanation is required to answer the second of the two questions posed above. In each of the previous years, we have observed the storage zone to undergo an annual cycle of aggradation and degradation corresponding to the rise and fall of the snowmelt hydrograph. To address this problem, we monitored sediment transport rates and changes in channel morphology in the lower 400 m of the storage zone throughout the 1986 field season. Bed load and instantaneous water discharge were measured at cross section 57 (Fig. 9), located in the middle of the study reach. Channel changes were determined from repeated surveys of 12 additional cross sections and 4 topographic surveys of the full reach using an electronic distance meter theodolite. Each of these topographic surveys produced an array of 700-900 points from which detailed contour maps and isometric plots of the channel were constructed.

Water and sediment discharge characteristics, June and July, 1986

The general trends in sediment transport during the 1986 snowmelt runoff were summarized for all sampling stations in the previous section. A more specific discussion of the water and discharge measurements at Cross Section 57 is included here for clarity and reference to the observed channel changes within the storage zone reach.

The 1986 snowmelt commenced in mid-May. An initial peak in early June was followed by another peak in mid-June, then steadily declining flow from late-June through July (Fig. 10). Bed load transport was highest in early-June and reflected the rise of snowmelt flows (Fig. 10). Through mid- and late-June bed load transport rates were proportionally lower for a given discharge. Through July, bed load transport rates were scattered about a relatively constant trend, but roughly mirrored the snowmelt flows (Fig. 10).

Although sediment transport is often, and conveniently related to discharge, unit stream power (the product of shear stress and velocity) has been widely adopted as a measure of transport capacity. Furthermore, unit stream power is dimensionally equivalent to unit bed load transport rate and therefore, a comparison can be made between power available to power expended in the form of a dimensionless ratio. This dimensionless ratio shows a near-constant trend through the snowmelt period (Fig. 11) and indicates that, on the average, only about 2 % (1/50) of the available stream power is used to transport bed load at the measurement section. This does not mean that unit stream power or bed load remain constant over the snowmelt period but that a uniform amount of power is expended in transporting bed load over the entire range of flows.

Adjustment of channel form, June and July 1986

Prior to rise of snowmelt, point bars were small, as shown on the initial topographic survey of 31 May (Fig. 12A). In early June, as snowmelt flows and sediment transport rates increased, the point bars grew in size by lateral and downstream accretion. Point bar growth was greatest in wide or low-curvature meander bends. The process of point bar growth began in the downstream part of the study reach and progressed upstream. This resulted in back-filling of the channel and a local reduction in slope at the bed load measurement site. The second topographic survey of 18 June, shows that there was a significant reduction of channel capacity as a result of point bar growth (Fig. 12B). Through late June and July, as snowmelt flows receded, the channel remained aggraded. Incision and erosion of point bars began in late July. Continued erosion through August produced a well defined channel with high relief point bars.

The adjustment of channel form is explained by the relationships between stream power (ω), bed load transport (q_s) and flow resistance (Darcy-Weisbach friction factor, *ff*) as given by:

$$\omega = \gamma dsv \qquad q_s \propto \omega^n \qquad ff = 8gds/v^2$$

where γ is the specific weight of water, d is the flow depth, s is the water surface slope, v is the flow velocity, and g is the gravitational acceleration. These equations can be manipulated to give:

$$q_s \propto \omega^n \propto k_1 (ff\, v^3)^n$$

and thus high rates of sediment transport correspond to a condition of high unit stream power and high flow resistance.

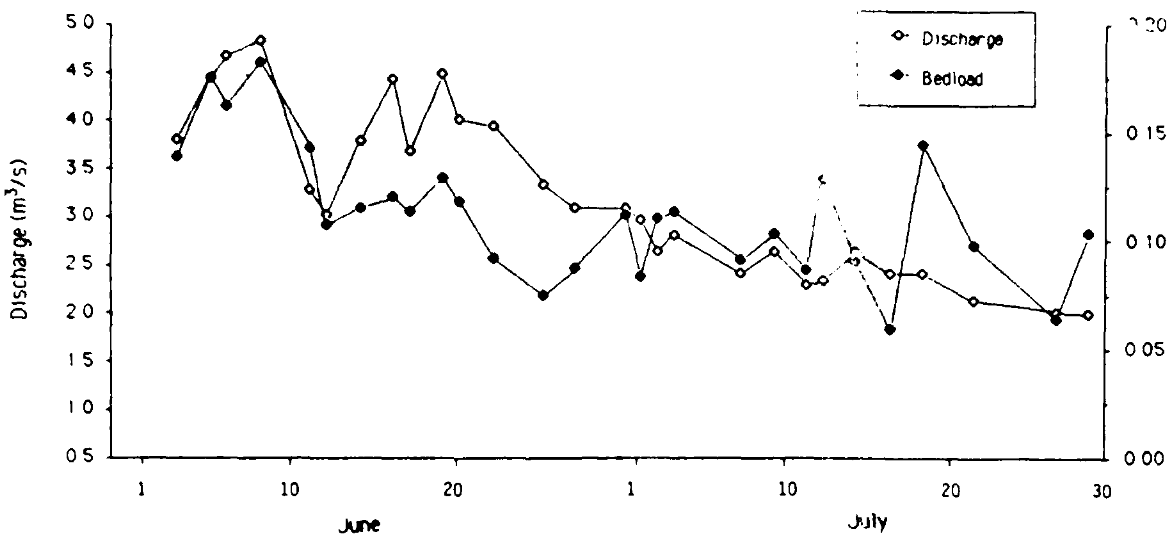


Figure 10. Comparison of water and bed load discharge at Cross Section 57 during the 1986 snowmelt period.

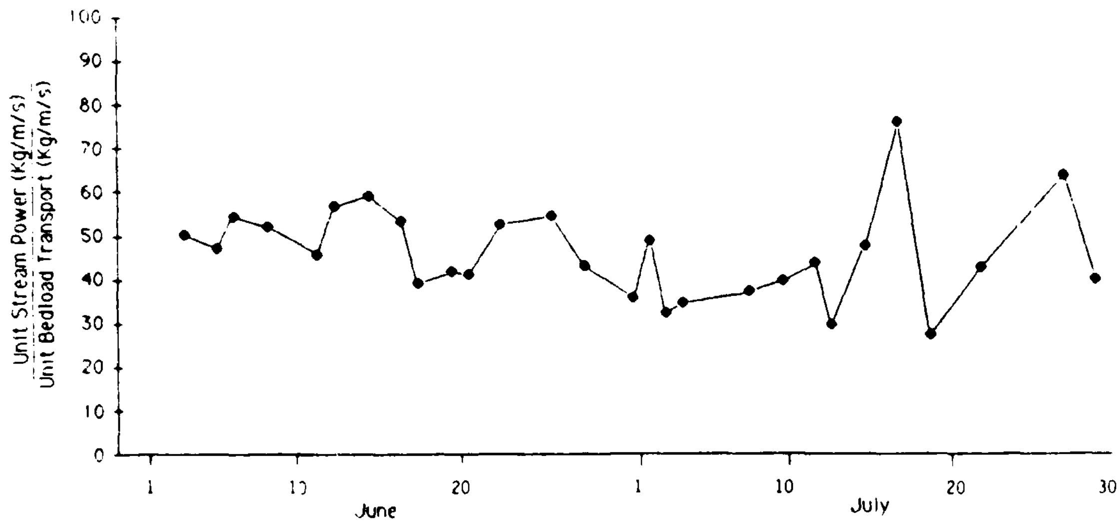


Figure 11. Dimensionless ratio of unit stream power and unit bed load transport rate during the 1986 snowmelt period at cross section 57.

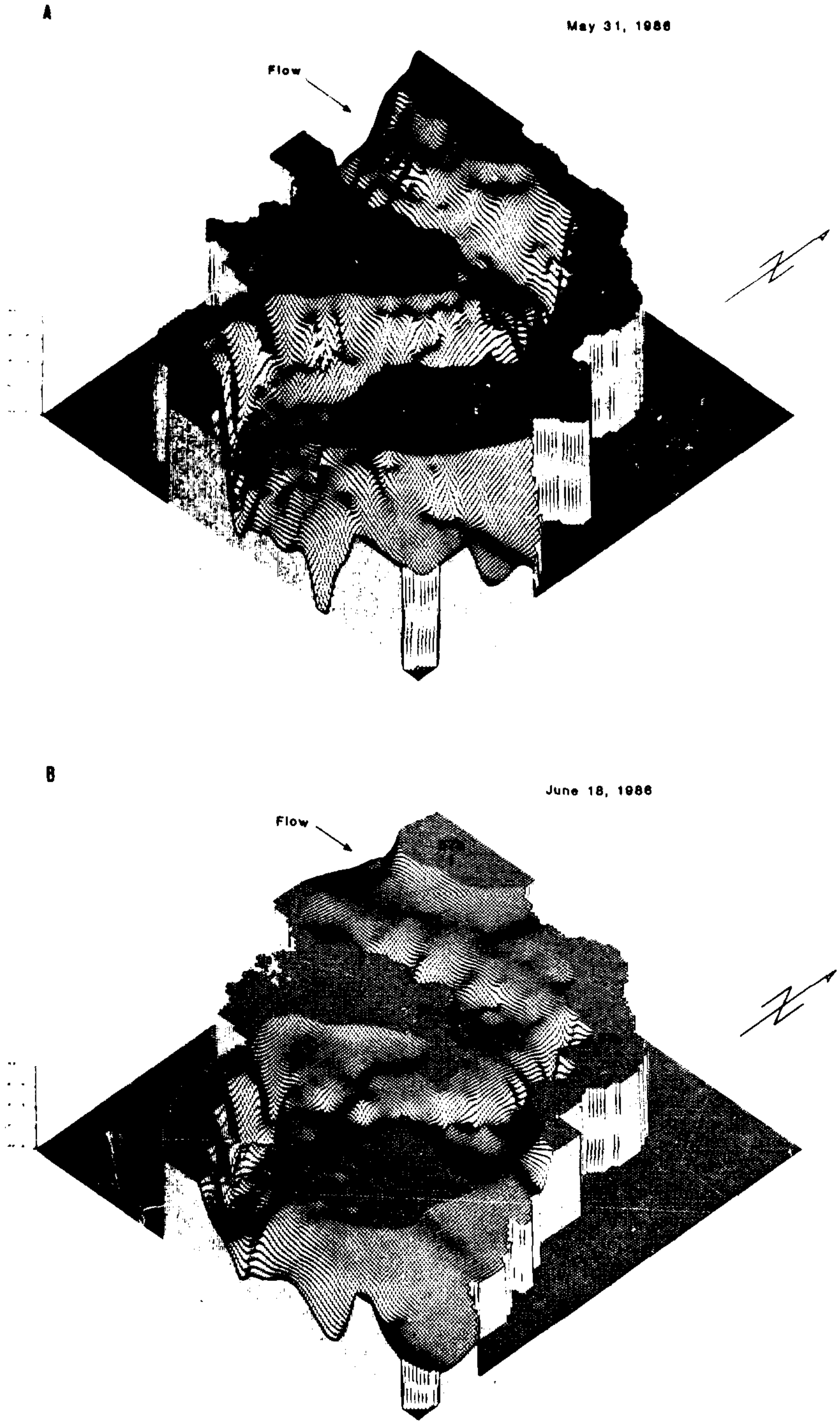


Figure 12. Isometric projection of bed topography within two bends of the storage zone reach (A) prior to the peak of snowmelt, May 31, 1986 and, (B) during the peak of snowmelt, June 18, 1986. Several cross section locations are shown for reference to Figs. 16 and 20. Note the growth of point bars between surveys.

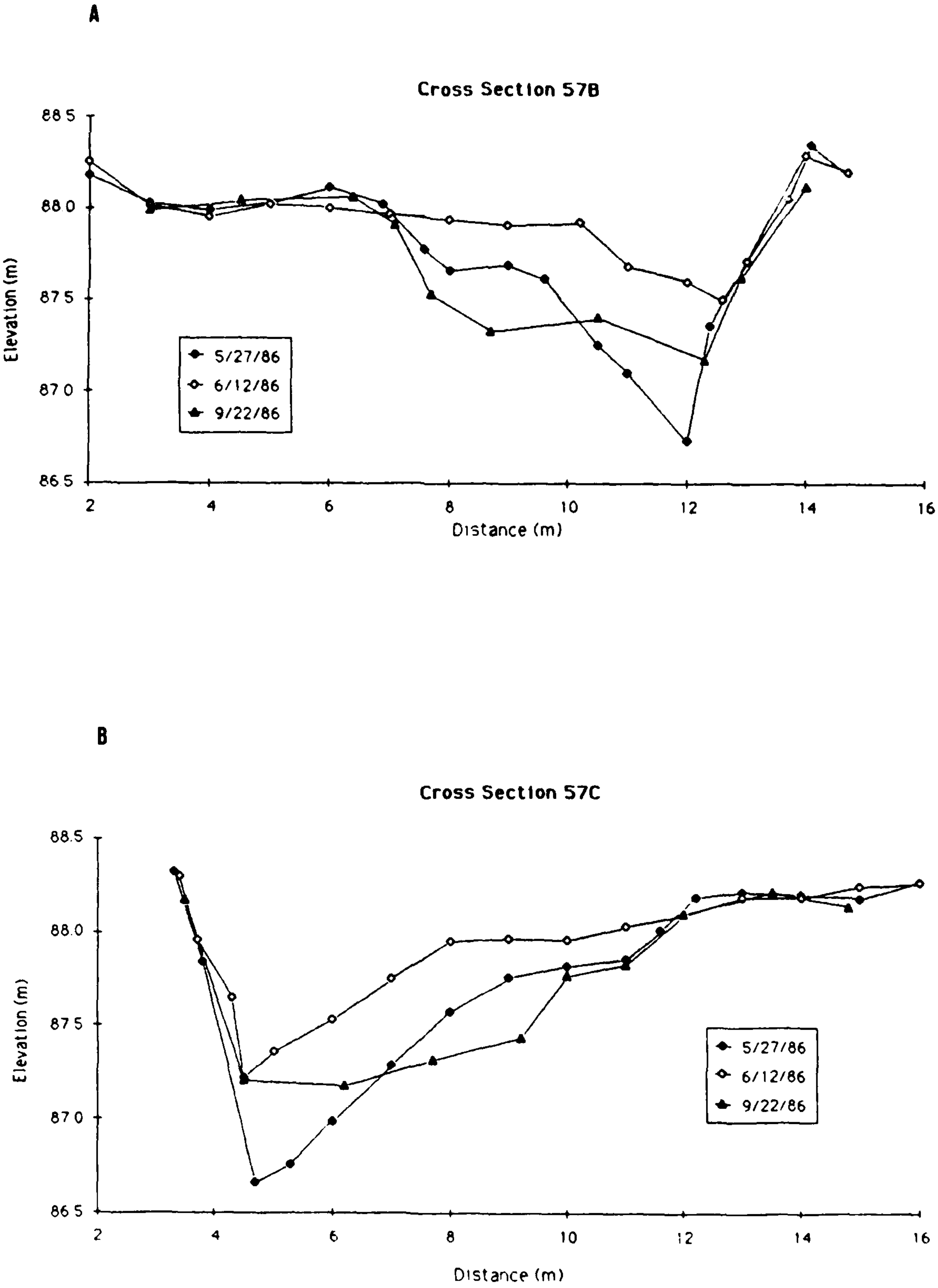


Figure 13. (A) Cross section 57b and (B) Cross section 57c, both within the storage zone reach. The channel aggraded an average of 0.5 m during the peak snowmelt period. The channel degraded during waning snowmelt period and channel cross sections became less assymetric.

During the initial rise of the snowmelt hydrograph, the stream flowed within a narrow, single thread channel bounded by the resistant outer banks of the pre-flood channel and the high relief point bars on the inner banks (Fig. 13A; 13B). In addition, much of the bed was armored with granule and pebble-sized sediment which, for shallow flows, offers greater flow resistance than a sand bed formed into dunes. Thus, during the rising stage, flow was entirely within-bank and, for a given discharge, flow resistance and stream power were relatively high (Table 5). As a result, the channel scoured and cross sections at point bars became more assymetric (Fig. 13A; 13B) and bed load transport rates were highest (Fig. 10). With a further increase in discharge, the pebble armor was mobilized and sediment was transported as dunes resulting in reduced flow resistance and a reduction in stream power. This promoted sediment deposition within the channel and the point bars grew in size (Fig. 13A; 13B). Furthermore, since flow was no longer confined to the channel, the outer banks exerted less of an influence on secondary (helical) flow circulation and, in turn, point bar growth was less constrained. The period of point bar growth was accompanied by declining bed load transport rates as sediment was being stored in the bars. As snowmelt receded, flow became more confined again, causing incision of the channel, re-establishment of the pebble armor and the development of high relief bed topography (Fig. 13A; 13B). The local slope at the bed load measurement site increased as the channel incised and bed load transport was maintained during waning snowmelt flows (Fig. 10).

Discussion

The processes of bar migration and stabilization have been examined in other field and experimental studies. Lewin (1976) described the movement and stabilization of alternate bars in an artificially straightened reach of the River Ystwyth in Wales. Alternate bars migrated through the upper part of the straightened reach, and had little influence on channel pattern. The bars stalled in the lower part of the reach and the channel developed a sinuous pattern because flow was shoaled over the high-relief, stabilized bars and deflected to the erodable banks. Lisle (1986) showed that bars were stabilized by large obstructions (logs, bedrock or an outer bank) which deflected the approaching flow away from the obstruction and caused a scour pool to form. The deflection angle influenced the strength of secondary flow circulation and its ability to scour the slipface of the bar and therefore, to stabilize it. Lisle (1986) also presented the experimental work of Kinoshita and Miwa (1974) who showed that bars were stable in bends constructed with deflection angles of more than 10^{o} of the flume centerline. In an experimental and field study, Ashmore and Parker (1983) found that the depth of scour at the confluence of braid anabranches increased as the angle between the anabranches increased. They noted the presence of back-to-back secondary flow cells within the scour holes and suggested that an increased confluence angle exerted a similar influence on scour depth as did a decreasing radius of curvature in a single-thread channel

The mechanisms of point bar growth in an typical meander bend are interpreted in light of the above discussion (Fig. 14). The bar is denoted by the stippled pattern, the pool by the hatched pattern and surface velocites are shown as vectors. We did not make oriented velocity measurements but those shown are consistent with the theoretical analysis of Smith and McLean (1983) and the field observations of Jackson (1975).

At low flow (upper diagram, Fig. 14), the point bar is exposed. Flow enters the bend parallel to the banks but, because of the bend curvature, impinges against the outer bank at increasingly sharper angles. At about the bend apex, this angle is sharpest and a scour pool forms at the outer bank. This produces an assymetric cross section, X-X', which is typical of bend apices (see Fig. 13B). Flow exiting the bend again becomes aligned parallel to the banks, no scour pool is present and, the channel has a rectangular form as shown by cross section Y-Y'.

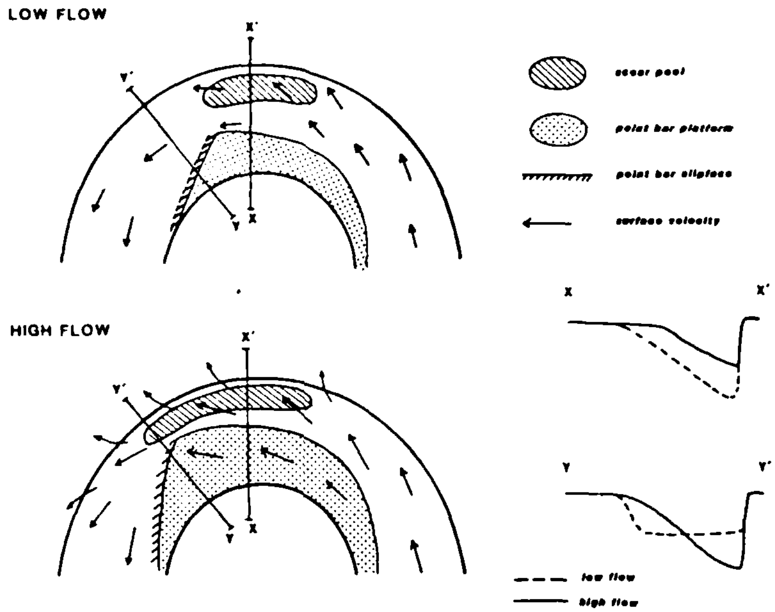


Figure 14. Schematic diagram of point bar, scour pool, and surface velocity vectors at low flow (upper) and high flow (lower). Point bar increases in size and scour pool grows downstream from low flow to high flow. Cross section adjustments at bend apex (X-X') and bend exit (Y-Y') are shown for each flow condition.

At high discharges (lower diagram, Fig. 14), the flow expands over the full channel width and the point bar becomes submerged. At the bend apex, flow impinging on the outer bank forms a scour pool. The depth of the scour pool, as discussed above, is a function of the flow orientation and the outer bank geometry. Because neither of these factors changed from low flow to high flow, the scour depth remains essentially the same as the discharge increases. As a result, the bed elevation to which the flow scours increases as the elevation of the water surface increases. This allows sediment to be deposited within the thalweg and accreted onto the point bar slope. The assymetry of cross section X-X', at the bend apex, is maintained but the channel has aggraded. In the downstream part of the bend, water flowing from across the point bar platform is also directed sharply against the outer bank. This causes scour and extends the pool further downstream. Thus, cross section Y-Y', which had a rectangular shape at low flow, becomes assymetric because of scour produced by the change in flow orientation.

During recessional flow, the patterns revert to the low-flow case. The downstream part of the point bar is truncated because of changing flow orientation. The scour pool decreases in size and the thalweg elevation at the bend apex is lowered as flow becomes confined.

The observations of point bar growth within this reach of Fall River have implications for the study of modern and ancient fluvial systems. Point bar accretion is generally viewed as a consequence of outer-bank erosion leading to meander migration and reworking of the floodplain (Wolman and Leopold, 1957). However, point bar growth in this reach was shown to be independent of outer-bank erosion and more a function of the flow conditions and the size and curvature of the bends. During the period of highest discharge and sediment transport, the channel was overwhelmed with sediment. If at that time, the channel were to be abandonded and its sediments preserved, the resulting deposits would include a clean, sandy channel fill encased in fine-grained floodplain sediments. A catastrophic influx of sediment, such as that which occurred at Fall River, may explain the presence of small, discontinuous sand bodies within the floodplain facies of ancient and modern fluvial sediments.

SUMMARY

Since the Lawn Lake flood, the geomorphic response of Fall River has been manifest by changes in channel geometry, in the composition of sediment forming the channel bed and in the quantity and composition of the sediment load. These changes, as determined from repeated measurements throughout the previous 4 field seasons, are summarized below. The most significant geomorphic adjustments occurred in the first summer following the Lawn Lake flood and changes which have occurred since that time have been far less significant. In the following discussion, the observed temporal trends are referenced to the initial measurements made at the start of the 1983 field season and include only those measurements made during the contiguous periods of peak snowmelt flow thereafter.

Adjustment of channel geometry

Channel adjustments of Fall River in Horseshoe Park can be summarized by changes in the average bed elevation at selected cross sections (Fig. 15). Each cross section is representative of a different reach of Fall River; Cross Section 10 is located on the alluvial fan, Cross Section 20 is located just downstream of the alluvial fan terminus, Cross Section 46 is located 500 m downstream of the U.S. Highway 34 bridge, Cross Section 57 is located in the downstream end of the storage zone and Cross Section 76 is just upstream of Ethel (Fig. 2).

Fall River has incised only slightly into the alluvial fan deposits. At Cross Section 10 (Fig. 15A), the average bed elevation decreased by 0.2 m during the 1983 snowmelt period and has since remained approximately the same. Incision of the fan deposits during the 1983 snowmelt was interrupted on several occasions by avulsions on the fan surface which resulted in filling of the channel. Within weeks however, this sediment was removed and the bed restored to its present elevation. Channel changes on the alluvial fan have not been significant since 1983 because of the declining sediment supply from Roaring River and because of the development of a bed material armor which is mobile only at the highest flows. Although it would not be appropriate to characterize the alluvial fan reach of Fall River as having "recovered" from the Lawn Lake flood catastrophy, it is surprising how stable this reach has become.

The sinuous, single-thread reach immediately downstream of the alluvial fan aggraded during the first month of the 1983 snowmelt period (Fig. 15B) when sediment delivery from the braided distributary network on the fan was very high. During the latter part of the 1983 snowmelt, the reduction in sediment supply from the alluvial fan resulted in degradation of the reach downstream. Average bed elevations at cross sections in this reach have remained approximately the same since the end of the 1983 snowmelt (Fig. 15B).

The most significant post-flood channel changes have occurred within a 2 kilometer-long sinuous reach downstream of the U.S. Highway 34 bridge. The high sediment loads of the 1983 snowmelt could not be conveyed through this reach and the channel aggraded to the level of the floodplain forming a discrete sediment storage zone. Aggradation in this reach reached a maximum during the latter part of the 1983 snowmelt period (Fig. 15C). During the 1984 snowmelt period, approximately 500 m of the upstream part of the storage zone degraded to the pre-1983 bed (Fig. 15C). Degradation was rapid because sediment supply from upstream was low in 1984 and because the sand-sized sediment comprising the channel fill was mobile at all flows which occurred during the 3-month snowmelt period.

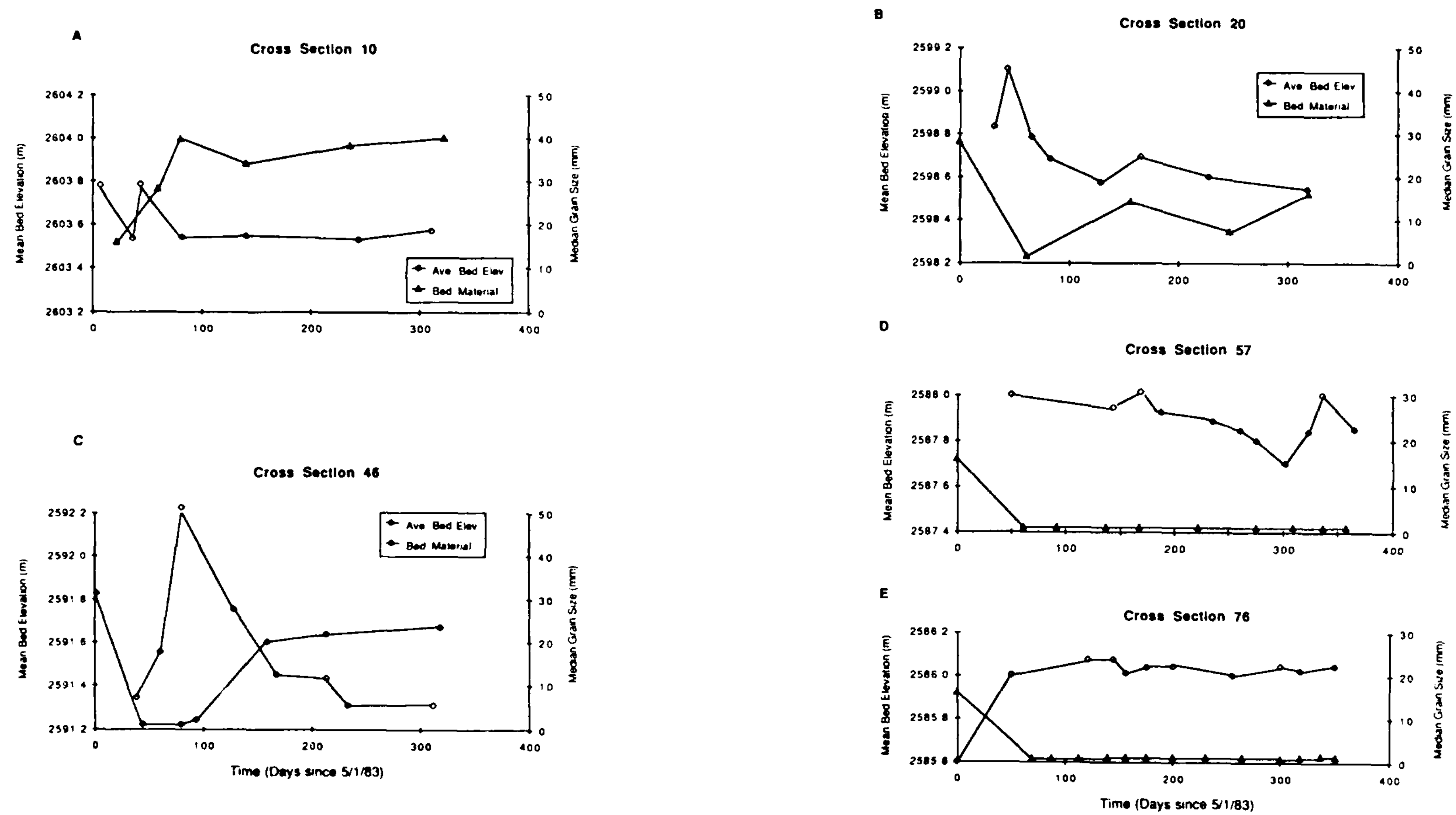


Figure 15. Changes in average bed elevation and bed material composition at selected cross sections within Horseshoe Park: (A) Cross Section 10, on the alluvial fan; (B) Cross Section 20, immediately downstream of the alluvial fan; (C) Cross Section 46, downstream of the U.S. Hwy. 34 bridge; (D) Cross Section 57, within the sediment storage zone; and (E) Cross Section 76 downstream of the sediment storage zone. Note that the mean bed elevations of Cross Sections 10, 20 and 46 stablized following the development of a cobble bed material armor; Cross Sections 57 and 76 remain aggraded with sand sized bed material.

Channel cross section measurements were not made in the downstream portion of the storage zone during the period when it was first observed to have formed in June and July, 1983. However, measurements made during subsequent snowmelt periods confirm that the downstream portion of the storage zone remains aggraded (Fig. 15D) and furthermore, that its terminus has remained in the same location. As discussed in the previous section, the downstream part of the storage zone undergoes a complex cycle of aggradation and degradation corresponding to the annual rise and fall of the snowmelt hydrograph. At high and moderate flows, sediment which is mobilized from the upstream end of the storage zone is deposited in the downstream end to form a quasi-braided channel. Progressive armoring of the bed during waning snowmelt flows results in a reduction of sediment supply and incision of downstream reaches to produce a well-defined meandering channel. However, the period of incision is not sufficiently long to fully exhume the pre-1983 bed and the channel remains aggraded with approximately 0.5 m of sediment (Fig. 15D).

The highly sinuous reach of Fall River between the storage zone and the downstream end of Horseshoe Park aggraded slightly during the 1983 snowmelt but has not undergone significant changes since that time (Fig 15E). Although sediment transport rates through this reach are perhaps 1000-times higher than before the Lawn Lake flood (Pitlick and Harvey, 1986), this reach maintains a sinuosity of 2.5 and remains single threaded. The ability of this reach to maintain high sediment transport rates without a significant change in planform is due to (1) the erosional resistance of the channel banks, and (2) the modulating effect of sediment storage in the reach immediately upstream.

Adjustment of bed material composition

Channel adjustments in Horseshoe Park have been intimately associated with changes in the composition of the sediment comprising the channel bed. Bed material samples have been taken at selected cross sections throughout the study area since the initiation of field studies in May 1983. Samples taken in the vicinity of each of the cross sections mentioned above reflect a fining of the bed material during periods when the channel was aggrading and a coarsening of the bed material when the channel was degrading (Figs 15A-15E).

The influx of sediment to a particular channel reach, whether during the Lawn Lake flood or during subsequent snowmelt periods, has resulted in aggradation of the channel. The rate at which the channel has degraded thereafter is dependent on the (1) quantity of sediment supplied from upstream reaches and (2) the frequency of flows which are competent to move the majority of the bed material. For example, the bed material at Cross Section 10, on the alluvial fan, coarsened during the latter part of the 1983 snowmelt (Fig. 15A), and the stability of the resulting armor layer has limited further degradation of the bed. Since, 1983, there has been little change in the bed material composition or bed elevation of channels on the alluvial fan because of the declining sediment supply from Roaring River and because of the stability of the bed material armor at all but the highest discharges.

In contrast, the bed material composition in the downstream reaches of Fall River (e.g. Fig 15D) has remained fine grained since the channel first aggraded in 1983. Sand-sized sediment eroded from the upstream end of the storage zone is deposited in the downstream end thereby maintaining fine-grained bed material and aggraded conditions.

Trends in Sediment Transport

The sediment load of Fall River has shown a response which is consistent with the observed changes in channel geometry and bed material composition as discussed above. Sediment transport measurements have been made throughout the previous 4 snowmelt periods at a site just downstream of the alluvial fan (Stanley, Fig. 2) and for 3 snowmelt periods at a site near the downstream end of Horseshoe Park (Ethel, Fig. 2). Together, these data document a spatially and temporally vairable response to the events which followed the Lawn Lake flood.

The amount of bed load transported past the sampling station downstream of the alluvial fan was greatest during the 1983 snowmelt (Fig. 16A). This was a period of record runoff but the high sediment loads in the first year following the Lawn Lake flood were primarily the result of channel incision on the alluvial fan. Bed load transport rates at this station have declined markedly in subsequent years. The declining sediment transport rates at this station are not due to a lack of high flows (Table 1) but are more the result of reduced sediment supply from Roaring River and the development of a static bed material armor layer which inhibits further incision of channels on the alluvial fan.

Bed load measurements made at the sampling station in the downstream end of Horseshoe Park contrast sharply with those made at the upstream station (Fig 16B). Sediment sampling was begun at Ethel in 1984 and measurements made in each of the subsequent snowmelt periods have varied greatly about a relatively consistent average. The sediment transported past this station is derived primarily from the storage zone immediately upstream. The sediment within the storage zone does not contain sufficient quatities of coarse bed material to allow the development of a static armor layer which would inhibit further bed degradation as on the alluvial fan. As a result, each year the storage zone erodes at its upstream end and in doing so, supplies sand and fine gravel-sized sediment to the reach downstream. This sediment is mobile under a wide range of flow conditions and, therefore, relatively high and consistent transport rates are maintained throughout the year.

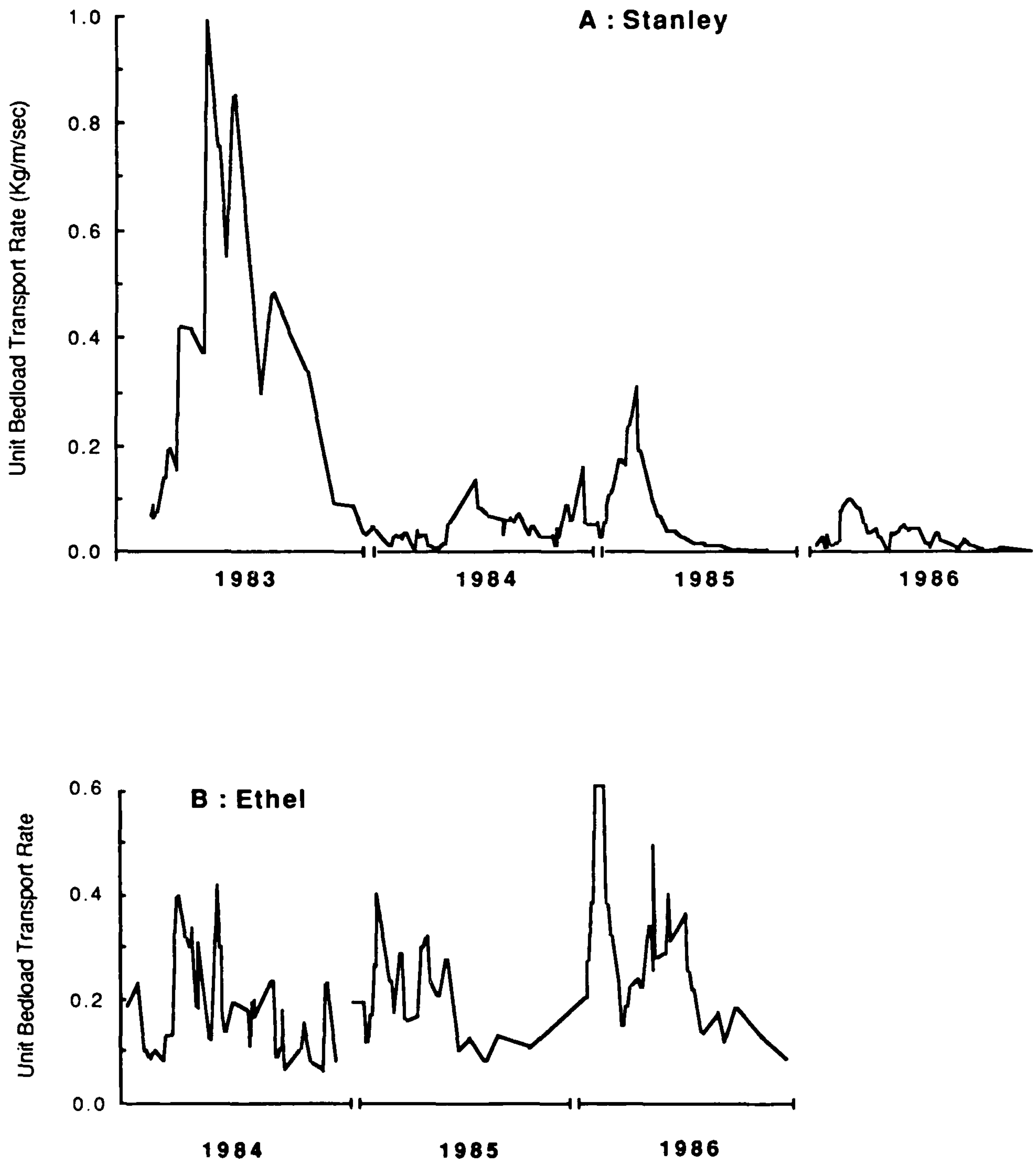


Figure 16. Trends in bedload transport rates as measured at two Fall River sampling sites. Data for Stanley includes measurements for the snowmelt runoff periods from 1983 through 1986; Data for Ethel includes measurements for the snowmelt runoff periods from 1984 through 1986.

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