Aerial Photograph/GIS Analysis and Field Studies of the Grand Valley and Ruby-Horsethief Canyon of the Colorado River

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INTRODUCTION

Problem Statement

It has been suggested in a number of recent reports (Stanford, 1994; Tyus, 1992; Osmundson and Kaeding, 1991) that the decline in native fish populations in the Colorado River system is due primarily to habitat loss and environmental changes associated with the construction of reservoirs and water diversions. This is a reasonable suggestion given that reservoirs modify flow hydrographs and reduce sediment loads, and these effects typically cause the river to become narrower downstream (Andrews, 1986; Williams and Wolman, 1984). However, until we began examining this issue, no one had actually determined the significance of channel change on the Colorado River nor had the link between flow regulation and channel change been well established. Our purposes then in undertaking geomorphic studies in the Grand Valley area and Ruby-Horsethief Canyon were to quantify historic (1937-present) changes in river morphology, to study the response of existing habitats to the present-day flow regimen and to predict the flow magnitude which will transport coarse sediment for habitat creation and maintenance. In previous reports (Van Steeter and Pitlick, 1994; Pitlick and Van Steeter, 1994), we have indicated that there is a tendency for the river to become narrower and for potential habitat to be lost when low or moderate flows occur several years in succession. And, although the long-term trend is toward a less complex channel, we have documented the formation of new habitat in areas that were changed by very high flows in 1983 and 1984.

This report describes work in progress aimed at defining historic changes in river morphology, effects of the 1993 and 1994 snowmelt flows on specific side channel/backwater habitats, and an evaluation of the threshold for transport of coarse bed material. A historic analysis of changes in channel morphology was completed by using historic and recent aerial photographs.

These photographs were digitized and measurements of channel change were calculated using a Geographic Information System (GIS). In addition to this analysis, three backwater sites were monitored before, during, and after the 1993 and 1994 spring runoff to determine the effects of these flows on the morphology of the sites. Finally, a series of measurements were taken at 6 sites in the Grand Valley near Grand Junction, Colorado and downstream in Ruby-Horsethief Canyon to evaluate conditions under which the coarse bed material of the Colorado River becomes mobile.

Setting

The study area covers approximately 91 kilometers (57 miles) of the Colorado River (Fig. 1). This area includes the 15 and 18 mile reach in the Grand Valley near Grand Junction, and Ruby-Horsethief Canyon. These areas are important habitat for both the Colorado squawfish (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*) (USFWS, 1987). In the Grand Valley, the Colorado River flows within a broad (~1 km) floodplain, although bank revetments and dikes limit channel change in many places. In the Ruby-Horsethief Canyon reach, the river is more confined by sandstone bedrock, but a small discontinuous floodplain borders much of the river. The median grain size (D_{50}) in both reaches is near 50mm.

The flow of the Colorado River in this area is dominated by snowmelt, but upstream water development also affects flows. For example, the average peak discharge of the Colorado River at Glenwood Springs has decreased by 28% when comparing separate time periods from 1931-1961 and 1962-1993, and the Colorado River at Cameo has decreased by 19% for roughly the same time period (Pitlick and Van Steeter, 1994). These data clearly indicate that reservoirs constructed in the last 30 years have had a significant impact on the natural flow regime.

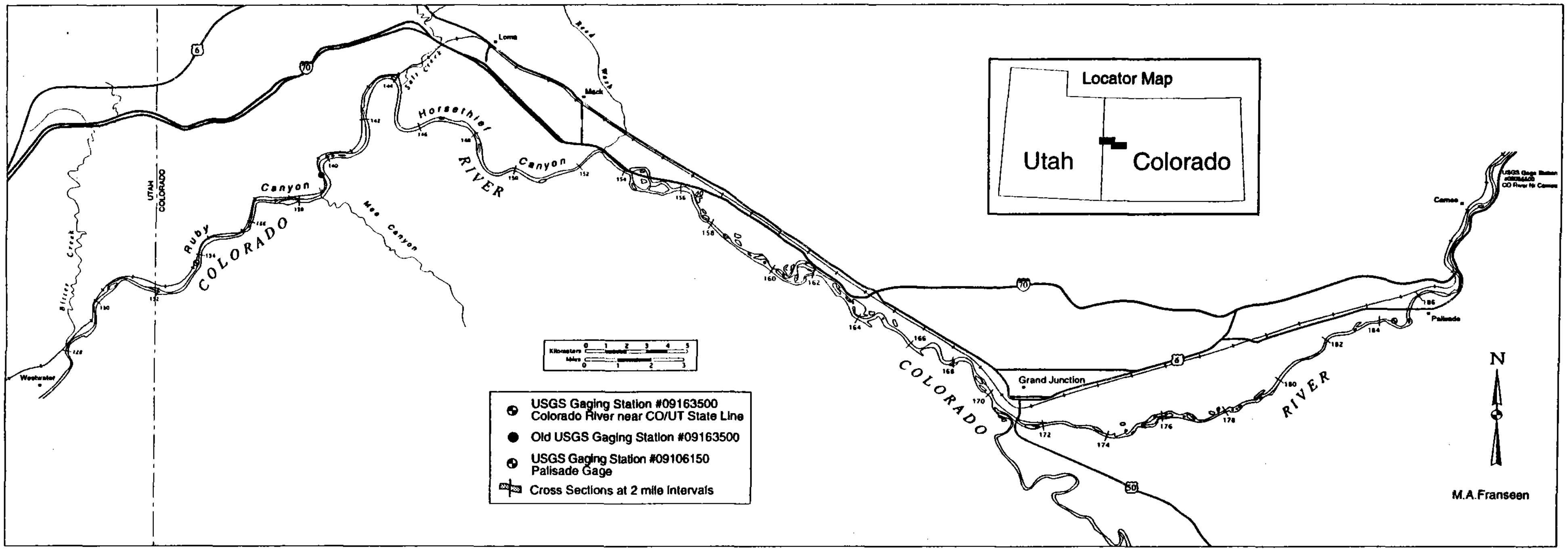


Figure 1. Location map of the study area

AERIAL PHOTOGRAPHY/GIS ANALYSIS

Methods

Aerial photographs of both the Grand Valley and Ruby-Horsethief Canyon were acquired. Photographs were chosen for 1937, 1954, 1968, and 1993. All photographs are black and white and 1:20,000 in scale. Photographs from 1937 and 1993 were taken at moderate flows of approximately 270 cms (9,500 cfs) at the state line gauge, and the 1954 and 1968 photographs were taken at low flows near 70 cms (2,500 cfs), thus limiting comparisons between photographs of similar flow. The outlines of specific features were digitized using a computer aided design system (ACAD), and then areas were measured with ARC INFO, a GIS software. Features included river banks, islands and emergent bars, and side channel/backwater areas which are defined as all areas other than the primary channel (Fig. 2). Our error estimates are ± 2% for water and island areas, and ± 10% for side channel/backwater areas.

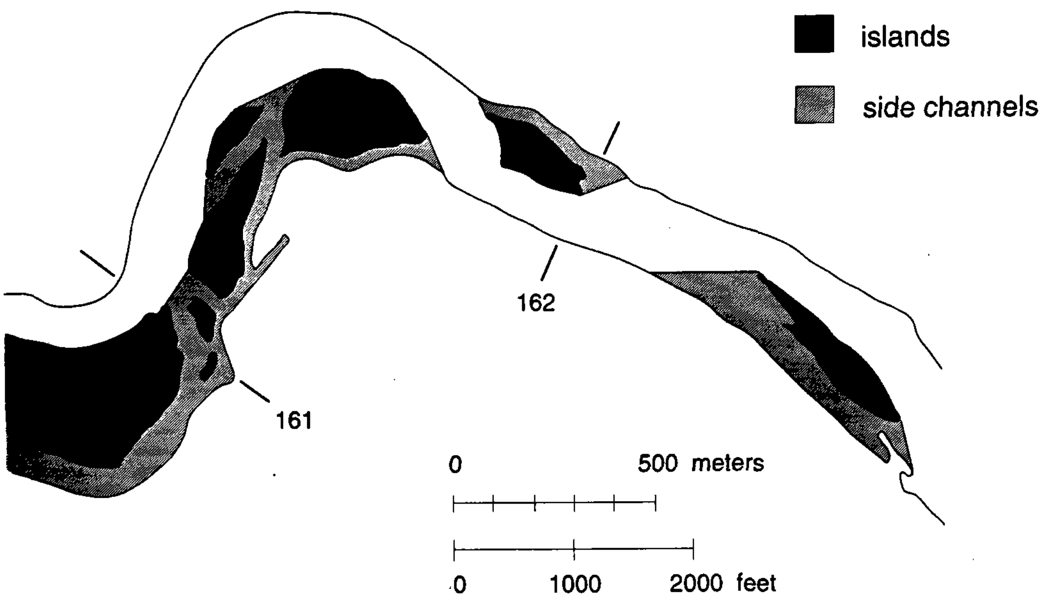


Figure 2. Map of main channel, islands, and side channel/backwater area

In a previous report (Van Steeter and Pitlick, 1994), we summarized similar results, but used photographs from 1986 since the 1993 set was not yet analyzed. This report focuses on results from this updated analysis as well as results for Ruby-Horsethief Canyon.

Results

Results for the Grand Valley showed that there was a substantial decrease in the area of channel features when comparing 1937 to 1993 and 1954 to 1968. The 1937-1993 analysis of the Grand Valley shows that there was a 19% decrease in water area, 12% decrease in island area, and a 26% decrease in side channel/backwater area (Fig. 3, Table 1). The 1954-1968 analysis showed a 12% decrease in water area, a 18% decrease in island area, and a 29% decrease in side channel/backwater area. See Van Steeter and Pitlick (1994) for more detail. Examples of channel change are illustrated in Figures 4 and 5.

Results of the analysis of Ruby-Horsethief Canyon for 1937-1993 show a decrease of 6.5% for water area, a 9.5% increase in island area, and a 23.2% decrease in side channel/backwater area (Fig. 6, Table 2). For 1954-1968 there was a 3.4% decrease in water area, a 4.2% increase in island area, and a 2.4% decrease in side channel/backwater area (Fig. 7, Table 3). Mile by mile maps of channel change are located in Appendix I and II.

Although it is somewhat useful to compare the two reaches by percent change, it is important to note that the area of channel features in the two reaches are very different. The Grand Valley reach has significantly larger water, island, and side channel/backwater areas than Ruby-Horsethief Canyon. When the average area of each channel feature per mile is calculated for the two reaches, it shows that water area is 21% greater in the Grand Valley, island area is 280% greater, and side channel/backwater area is 175% greater than in Ruby-Horsethief Canyon.

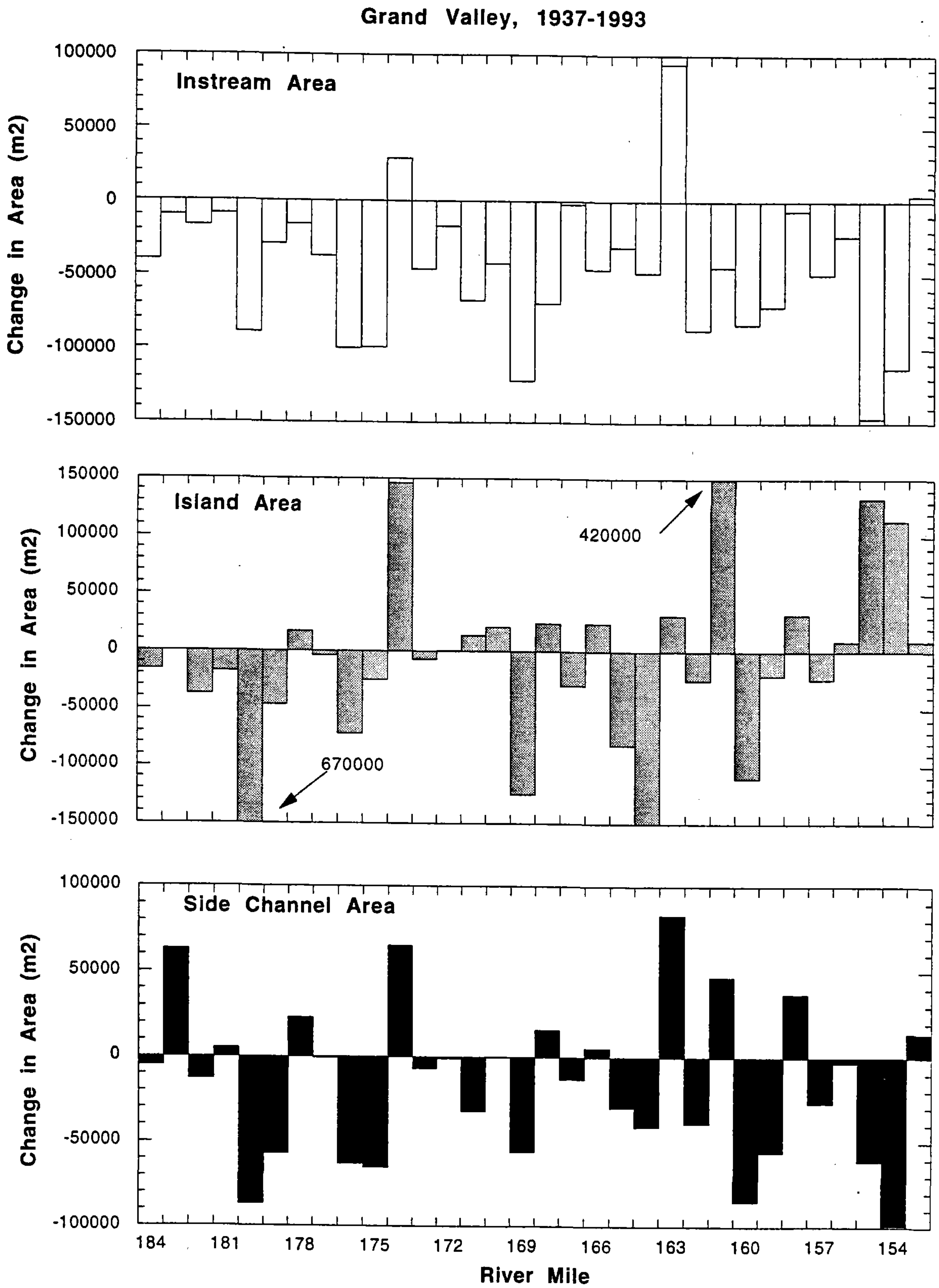


Figure 3. Changes in instream area, island, and side channel area in the Grand Valley between 1937 and 1993

Table 1. Change in channel features in the Grand Valley, 1937-1993.

RM	Instream Water Area (m^2) 1937	Instream Water Area (m^2) 1993	Island Area (m^2) 1937	Island Area (m^2) 1993	Side Channel Area (m^2) 1937	Side Channel Area (m^2) 1993
184	176000	136000	26000	10000	16000	11000
183	179000	169000	91000	91000	16000	79000
182	167000	150000	38000	500	15000	2000
181	160000	151000	23000	5000	9000	14000
180	240000	151000	674000	4000	97000	10000
179	230000	201000	115000	68000	83000	26000
178	177000	161000	5000	22000	10000	33000
177	139000	102000	4000	0	600	0
176	258000	158000	200000	128000	81000	18000
175	248000	149000	180000	155000	90000	25000
174	176000	205000	15000	161000	33000	98000
173	171000	125000	14000	7000	13000	6000
172	146000	129000	700	1000	2000	1000
171	231000	164000	171000	185000	75000	43000
170	300000	258000	130000	151000	60000	60000
169	293000	171000	150000	25000	95000	39000
168	274000	205000	170000	194000	75000	91000
167	217000	215000	49000	19000	28000	15000
166	227000	181000	12000	36000	22000	27000
165	258000	227000	164000	82000	79000	49000
164	229000	181000	177000	24000	85000	44000
163	231000	325000	15000	46000	22000	105000
162	275000	188000	34000	9000	67000	28000
161	265000	221000	115000	535000	65000	112000
160	274000	191000	214000	103000	129000	44000
159	295000	224000	191000	170000	111000	55000
158	235000	229000	25000	57000	23000	60000
157	239000	190000	68000	44000	54000	27000
156	186000	163000	7000	16000	11000	8000
155	394000	247000	187000	320000	153000	92000
154	375000	262000	723000	837000	198000	99000
153	210000	214000	0	9000	6000	20000
Total:	**7475000**	**6043000**	**3987700**	**3514500**	**1823600**	**1341000**
Percent Change:	**-19 %**		**-12%**		**-26%**	

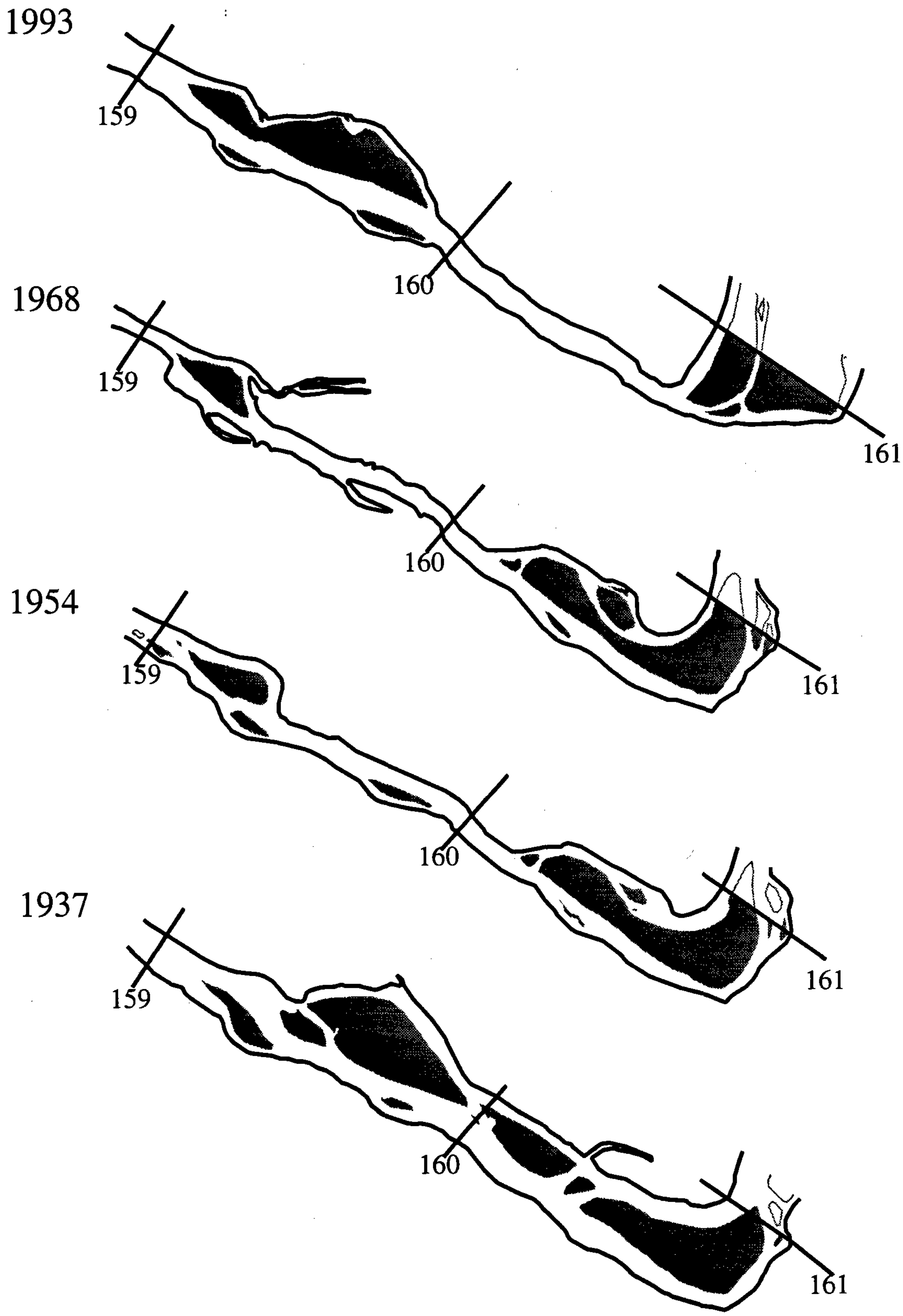


Figure 4. Maps of historic channel change in the Grand Valley

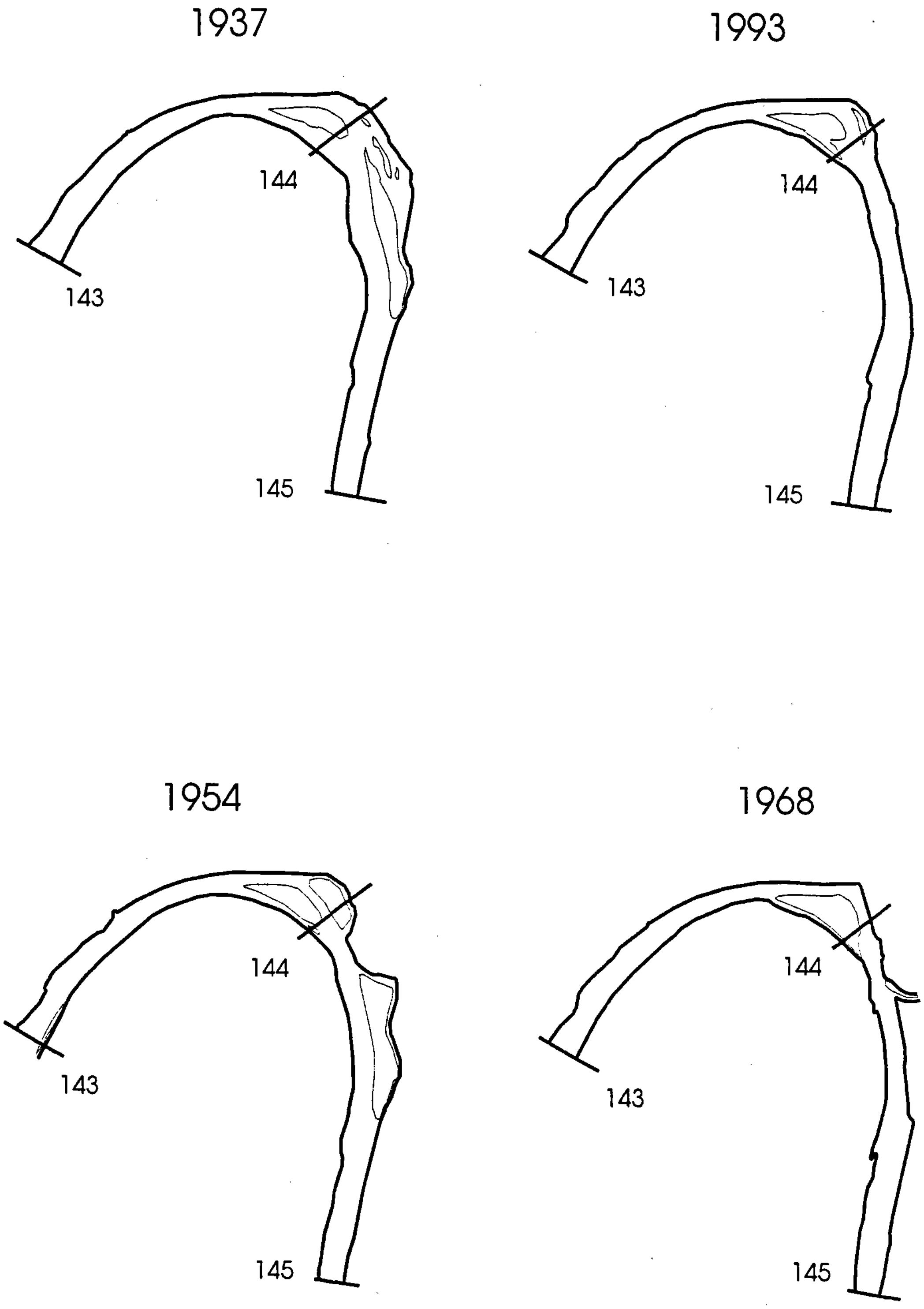


Figure 5. Maps of historic channel change in Ruby-Horsethief Canyon

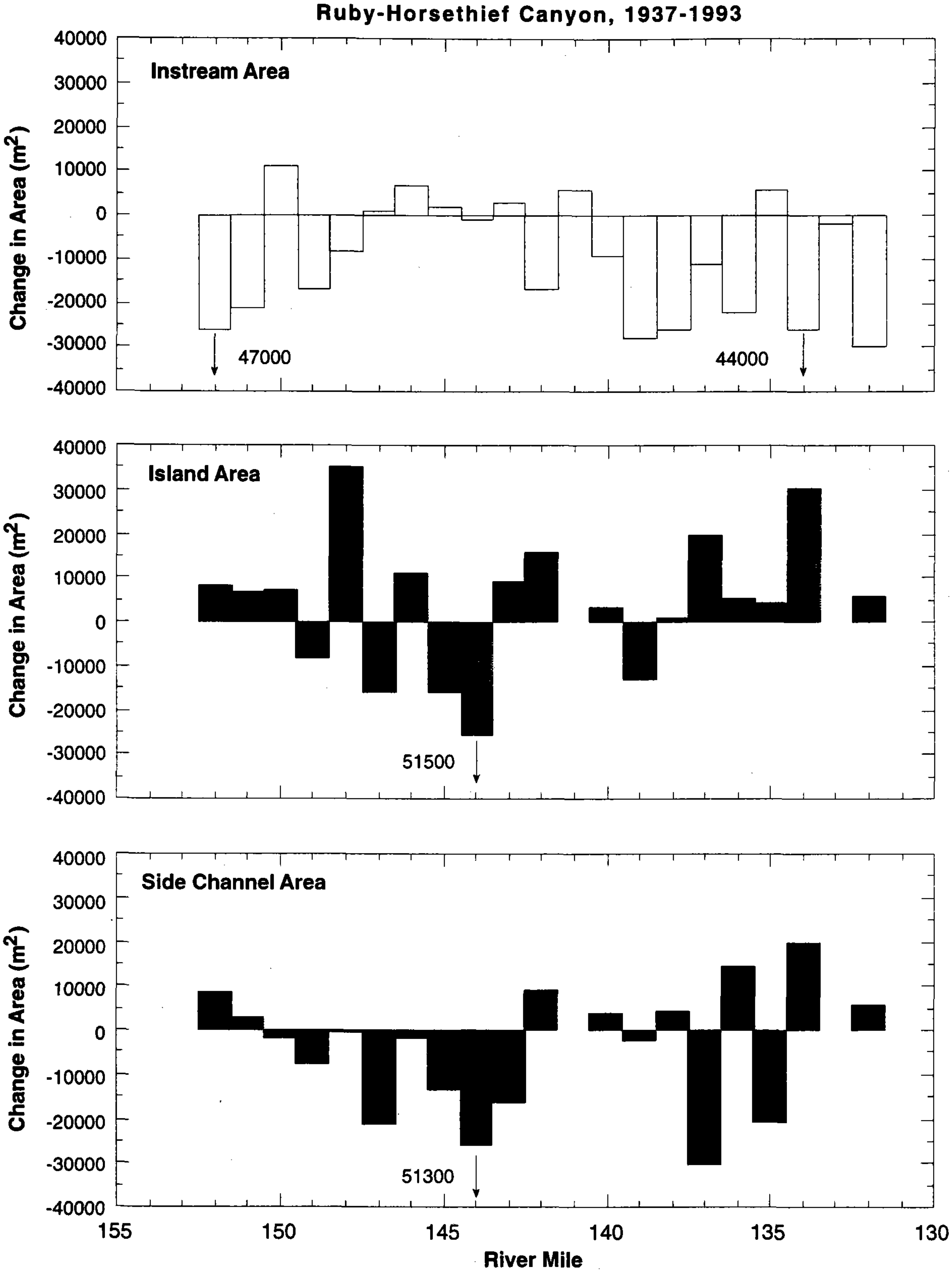


Figure 6. Changes in instream area, island, and side channel area in Ruby-Horsethief Canyon between 1937 and 1993

Table 2. Change in channel features in Ruby-Horsethief Canyon, 1937-1993.

	Instream Water Area (m^2)		Island Area (m^2)		Side Channel Area (m^2)	
RM	1937	1993	1937	1993	1937	1993
152	203000	156000	20400	28500	8800	17600
151	191000	170000	0	6600	0	2800
150	162000	173000	25800	33000	19400	17700
149	209000	192000	8300	0	7600	0
148	163000	155000	38700	73800	39700	39400
147	168000	169000	104700	88700	31800	10600
146	178000	185000	7500	18500	18400	16300
145	170000	173000	15900	0	13500	0
144	206000	205000	52300	800	56500	5200
143	160000	164000	20600	30000	32500	16000
142	204000	187000	37400	53200	30800	40200
141	166000	171000	0	0	0	0
140	168000	159000	31500	34900	55200	59000
139	195000	168000	14400	1300	9300	6600
138	201000	175000	0	1100	0	4600
137	146000	134000	195300	215100	66700	36400
136	156000	135000	2000	7400	0	14400
135	139000	145000	39700	44000	31400	10800
134	222000	178000	0	30500	0	19600
133	156000	154000	0	0	0	0
132	216000	186000	1600	7300	3200	9200
Total:	**3779000**	**3534000**	**616100**	**674700**	**424800**	**326400**
Percent Change:	**-6.5 %**		**9.5 %**		**-23.2%**	

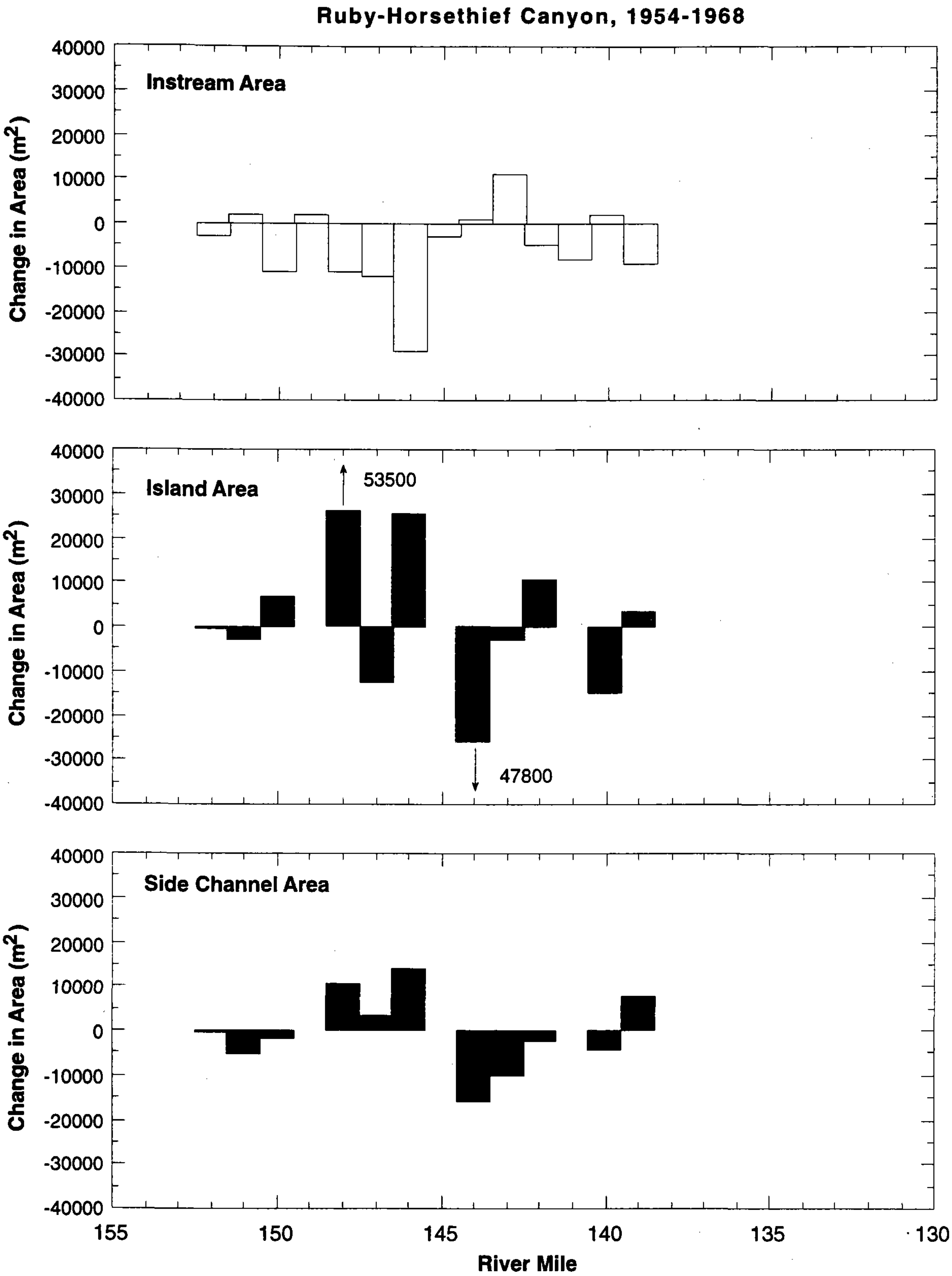


Figure 7. Changes in instream area, island, and side channel area in Ruby-Horsethief Canyon between 1954 and 1968

Table 3. Change in channel features in Ruby-Horsethief Canyon, 1954-1968.

	Instream Water Area (m^2)		Island Area (m^2)		Side Channel Area (m^2)	
RM	1954	1968	1954	1968	1954	1968
152	142000	140000	700	400	3300	3100
151	148000	150000	2700	0	5300	100
150	147000	136000	46000	52800	12000	10200
149	181000	183000	0	0	0	0
148	124000	113000	53800	107300	16200	26800
147	131000	119000	128300	115700	8700	12100
146	162000	133000	7300	33000	1800	15700
145	159000	156000	0	0	0	0
144	177000	179000	54400	6600	20300	4500
143	142000	153000	37600	34700	18900	8600
142	150000	145000	64000	74700	38700	36400
141	158000	150000	0	0	0	0
140	138000	139000	58500	43600	52100	47900
139	163000	154000	0	3500	200	8000
Total:	**2122000**	**2050000**	**453300**	**472300**	**177500**	**173200**
Percent Change:	**-3.4 %**		**4.2 %**		**-2.4%**	

In general, there was a decrease in water area and side channel/backwater area for both areas, but an increase in island area in the Ruby-Horsethief Canyon reach. Since the Grand Valley reach is alluvial, it would be expected that channel changes in this reach would be more significant than in the Ruby-Horsethief Canyon where general channel morphology is strongly controlled by bedrock. The increase in island area in Ruby-Horsethief Canyon is probably due to the accretion of sediment to pre-existing islands. In the Grand Valley it is likely that this same process has occurred, but the islands have accreted to the floodplain.

Although there was an overall decrease in side channel/backwater area through time, some reaches show an increase in area. Some of these reaches include areas which were changed in 1983 and 1984 when high flows breached dikes and flooded abandoned gravel pits. The current affect of these flows on the 1993 photographs is unclear, but it is likely that loss of side channel/backwater area would be greater if these flows had not occurred. The 1954-1968 analysis is perhaps a better measure of general channel change since there were no extreme flow events during the period. During this period, the mean annual flow was exceeded at the Cameo gauge only 5 times, which suggests that when peak flows are below average for several years in succession, the channel becomes narrower and there is a systematic loss of side channel/backwater habitat (Pitlick and Van Steeter, 1994).

COMPARISON OF 1993 AND 1994 FLOWS

The flows of 1993 and 1994 provide a good example of the year to year variability in runoff of the Colorado River. The two gauges used for this summary are: 1) the Colorado River below the Grand Valley diversion near Palisade, at the most upstream end of the study area; and 2) the Colorado

River near the Colorado-Utah state line, near the downstream end of the study area. The Palisade gauge is at the head of the Grand Valley above the confluence of the Gunnison River, and the state line gauge is in Ruby-Horsethief Canyon (Fig. 1).

The flows of 1993 were above average. Discharge began to increase in late April, flows increased sharply in the beginning of May, and the peak flow of 1,250 cms (44,300 cfs) occurred on May 28 which has a return period of approximately 6 years (Fig. 8). Runoff continued into the middle of August. In contrast, the flows of 1994 were below average, with a return period of the peak flow of only 1.16 at the state line gauge. Flows did not increase substantially until the second week in May, flows peaked at 370 cms (13,100 cfs) on June 2, and runoff ended by the first week in July. Flows at the Palisade gauge show similar trends and recurrence intervals, but are of a smaller magnitude since they are upstream of the Gunnison River. The combined effect of both the difference in magnitude and duration of flow is evident in the mean annual discharge of the river in the two years. In the 1993 the mean annual discharge was 240 cms (8,490 cfs), and in 1994 it was only 130 cms (4,590 cfs).

The different flow magnitudes of these two years were ideal for our studies of the affects of flow on channel morphology and sediment transport. It allowed us to document stage-discharge relationships near bankfull discharge in 1993, and to measure the effects of high and low flow years on backwater morphology.

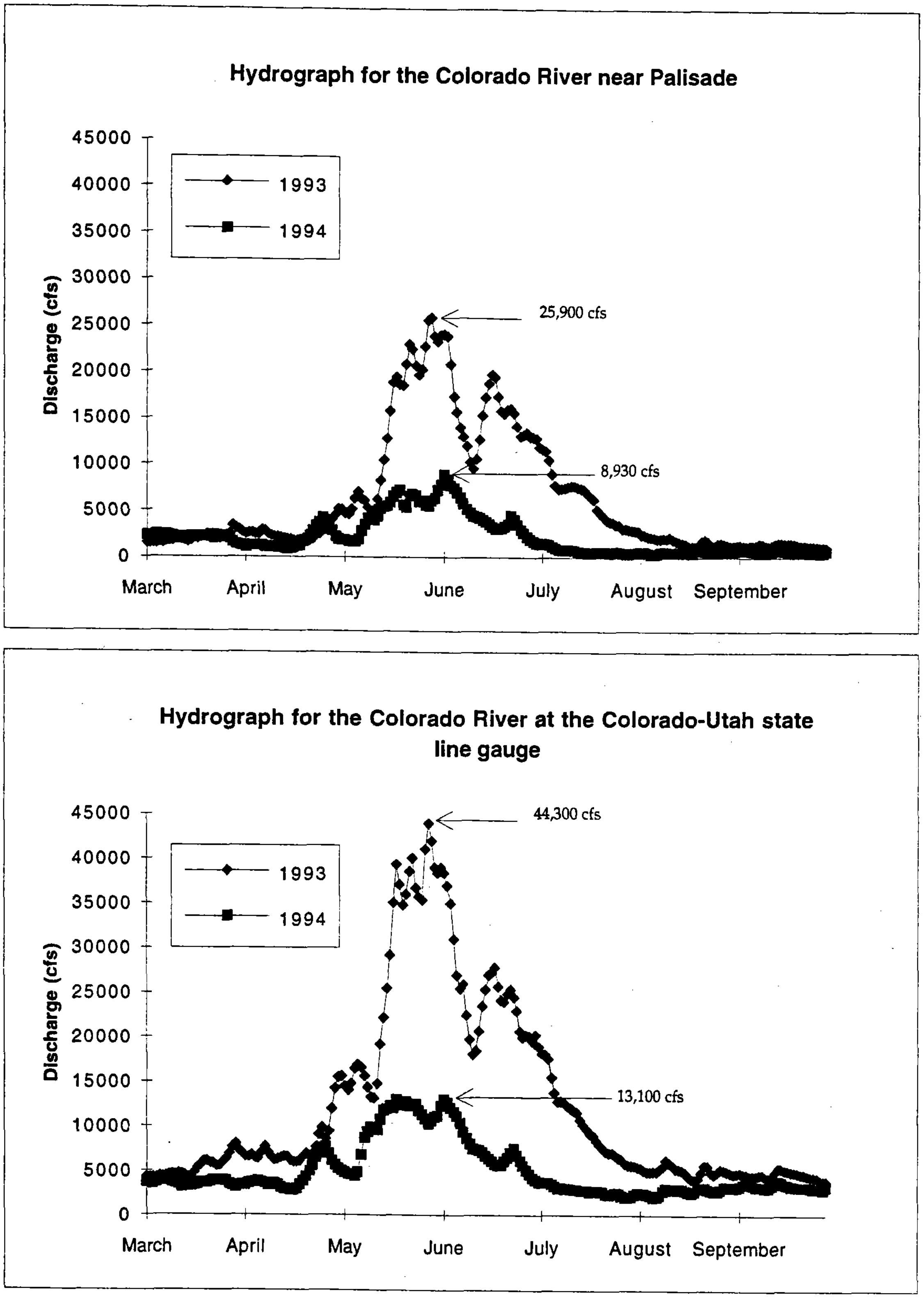


Figure 8. Hydrograph of 1993 and 1994 at the Palisade and State Line gauges

1993 AND 1994 FIELD STUDIES

Side channel/backwater habitats were the focus of the field study due to their importance to both the adult and larval stages of the Colorado squawfish and razorback sucker. Backwater morphology is partly dependent upon the flow regime which controls the scour and fill of sediment. The high flows of spring generally cause the backwater to become a side channel and fine sediment that has accumulated on the bed is scoured. Some researchers theorize that river regulation has decreased flows and caused a net filling of these areas with sediment (Osmundson and Kaeding, 1991; Graf, 1978). The relatively high (1993) and low (1994) peak discharges of the two years allowed us to document the effects of flow magnitude on backwater morphology.

Methods

Three side channel/backwater sites were chosen and 25 cross-sections of bed topography were surveyed before, during, and after the peak flows of 1993 and 1994. All cross-sections were permanently marked with rebar or metal fence posts. Standard surveying techniques were used to measure cross-sections in areas of shallow flow. In deeper areas such as the main channel, cross-sections were surveyed from a boat outfitted with depth sonar (Van Steeter and Pitlick, 1994). Characteristics of the three sites are summarized in Table 4.

Table 4. Summary of Backwater Field Site Characteristics

location (river mile)	D_{50} (mm)	number of cross-sections	characteristics at different flows low	med	high
Site 1 (162.5)	50	6	SB	BW	SC
Site 2 (159.9)	48	10	BW	SC	SC
Site 3 (175.5)	55	8	BW	BW	SC

SB: stranded body of water
BW: backwater
SC: side channel

Results

The 1993 flows caused scour of 0-2.5m of fine sediments from the mouth of the backwater sites, but few changes occurred at the upstream ends where the substrate is primarily gravel. Fine sediments were deposited along the banks at most cross-sections, and vegetation was generally abraded but not uprooted. Scour at the mouth of these backwaters is important for maintaining fish access at low flows. It appears that the high flows of 1993 were important for scouring backwater mouths, but one year of high flow does not appear to be enough to greatly change the morphology of the upstream end or to uproot existing vegetation.

The flows of 1994 were low and only small amounts of scour and deposition were observed. There was 0-1.7m of deposition of fine sediment at the mouths of these backwaters, but other changes were minor. These trends are most evident at site 3 (Fig. 11). Site 2 showed fewer changes because it is a side channel even at moderate flows and substantial amounts of fine sediment do not accumulate (Fig. 10). Site 1 shows minimal changes at its mouth because of dense root mats of grasses which stabilize sediment (Fig. 9).

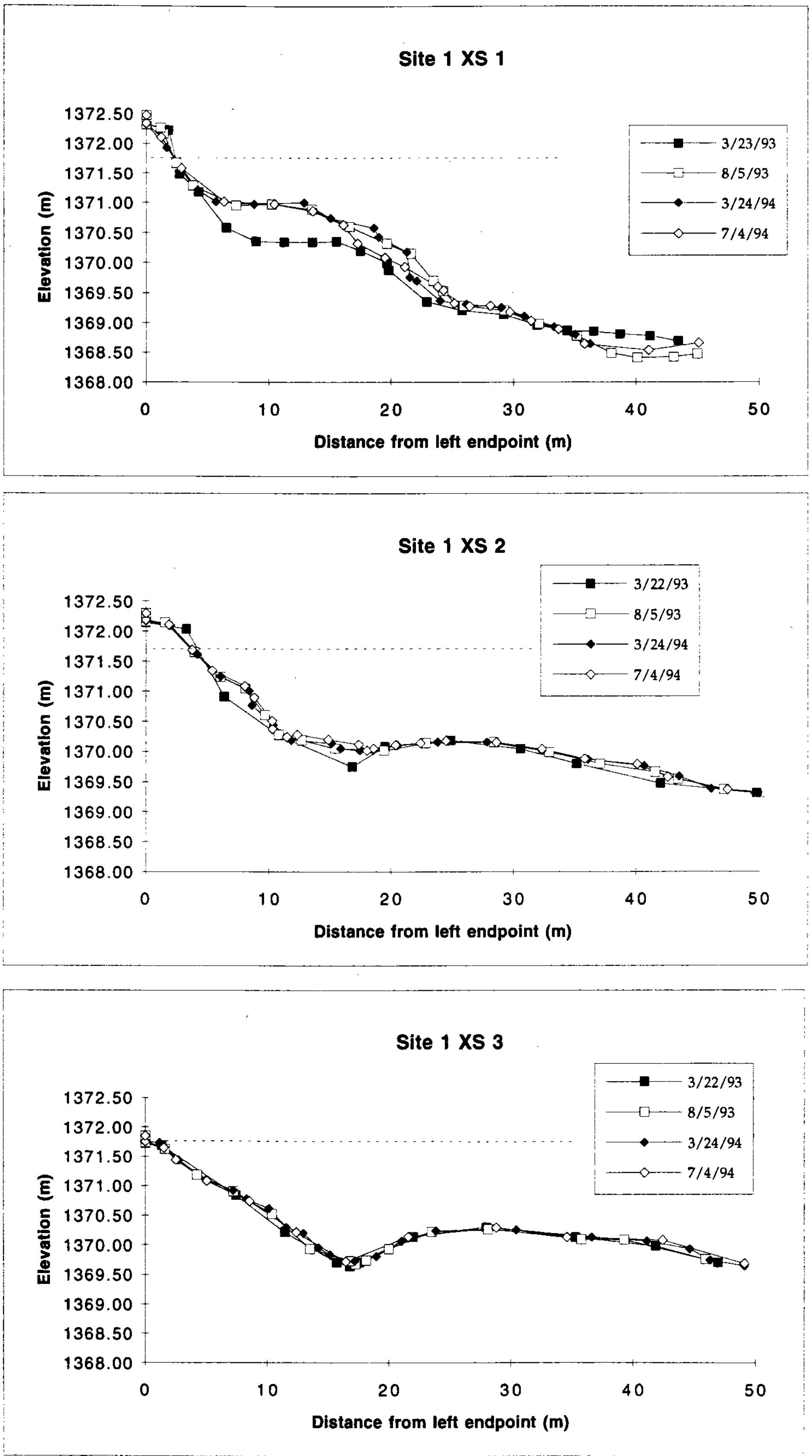
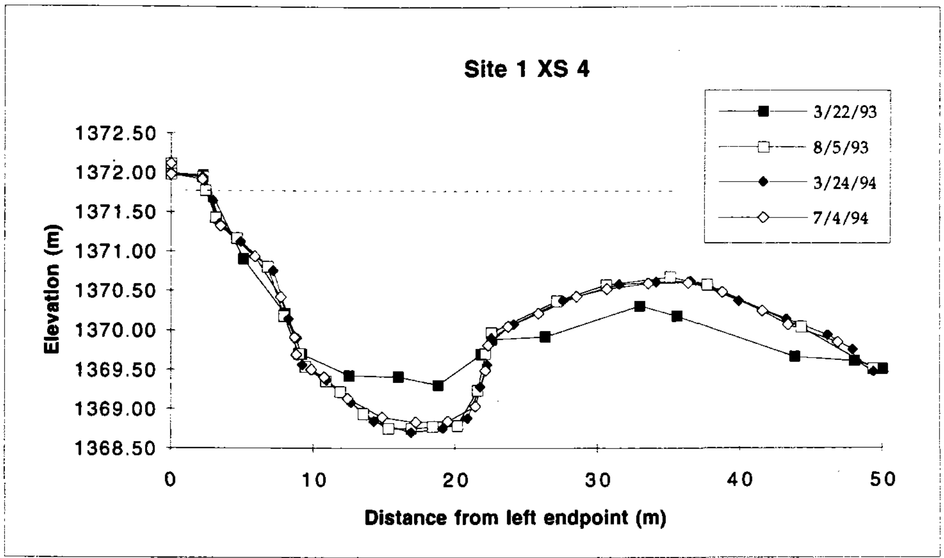


Figure 9. Channel cross-sections of Site 1. Cross-sections 1-3 are at the upstream end and 4-6 are at the downstream end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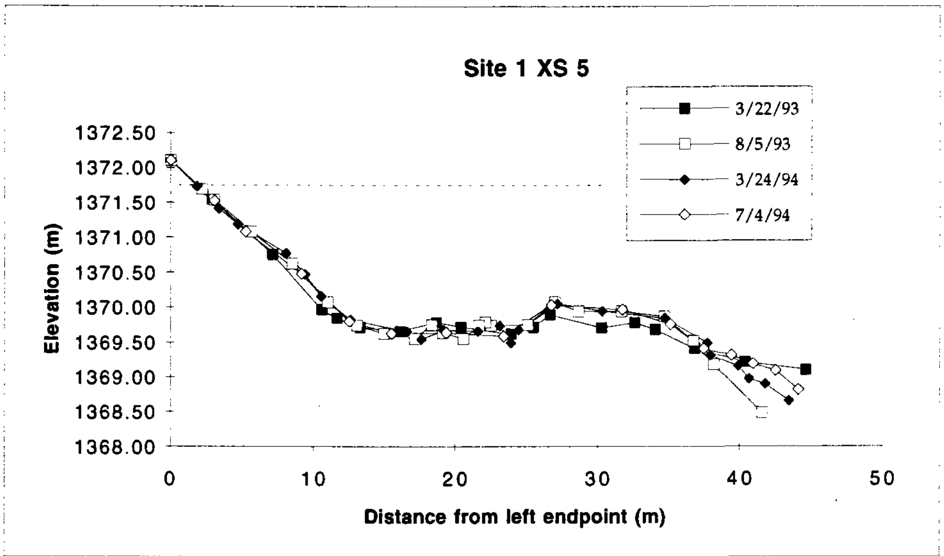
3/22/93
8/5/93
3/24/94
7/4/94
Elevation (m)
1372.50
1372.00
1371.50
1371.00
1370.50
1370.00
1369.50
1369.00
1368.50
0
10
20
30
40
50
Distance from left endpoint (m)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8/5/93
3/24/94
7/4/94
Elevation (m)
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1371.00
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1369.50
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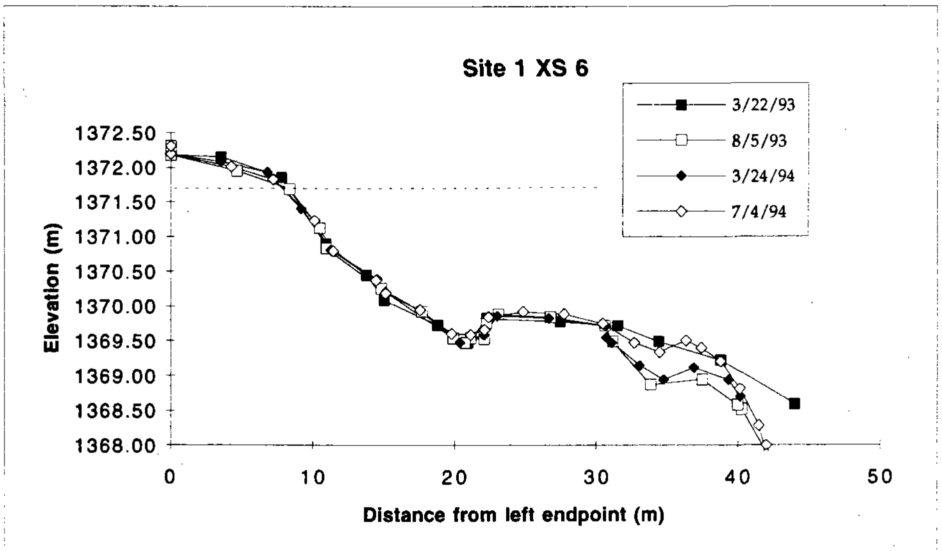
10
20
30
40
50
Distance from left endpoint (m)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7/4/94
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20
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40
50
Distance from left endpoint (m)

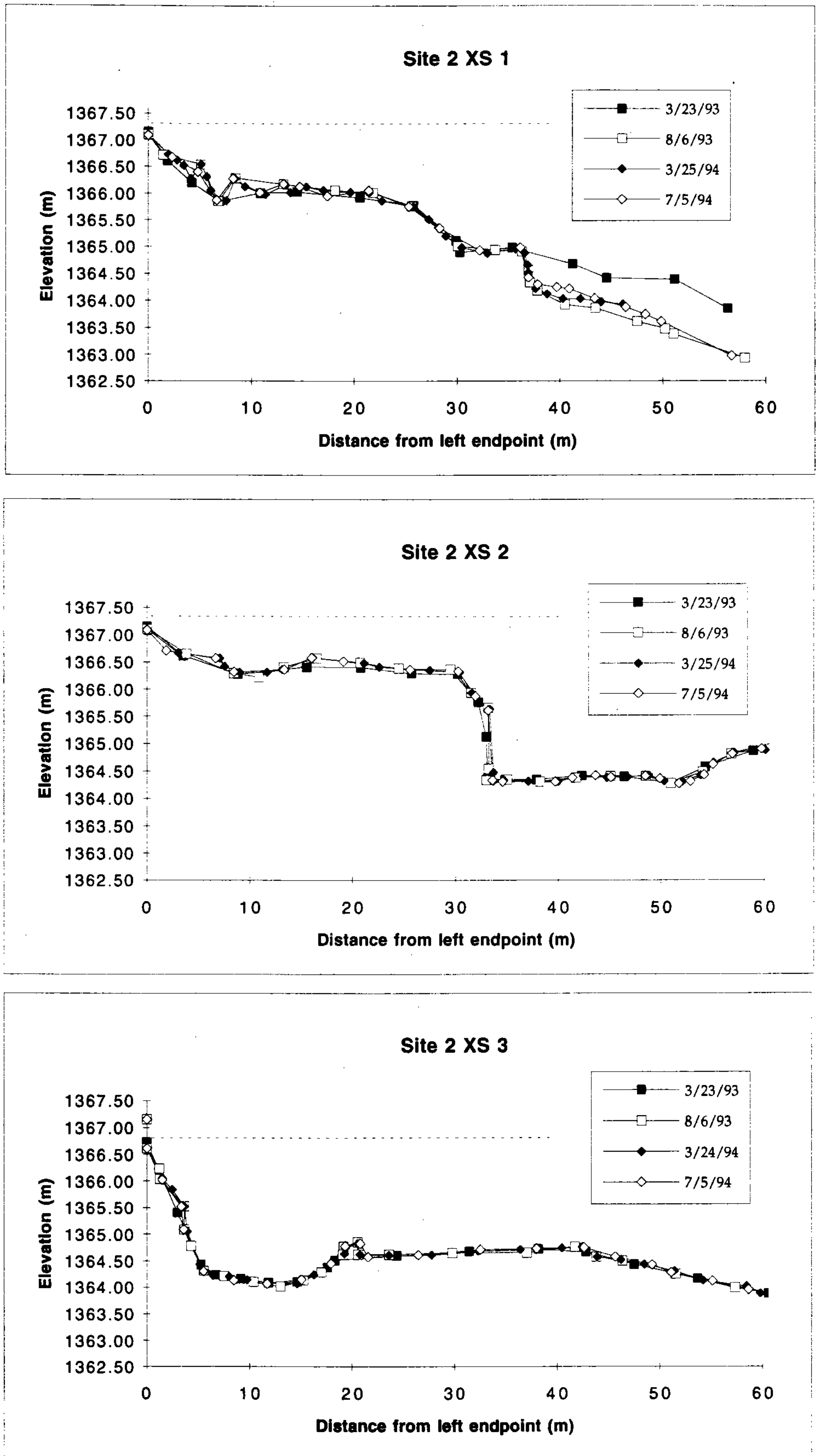
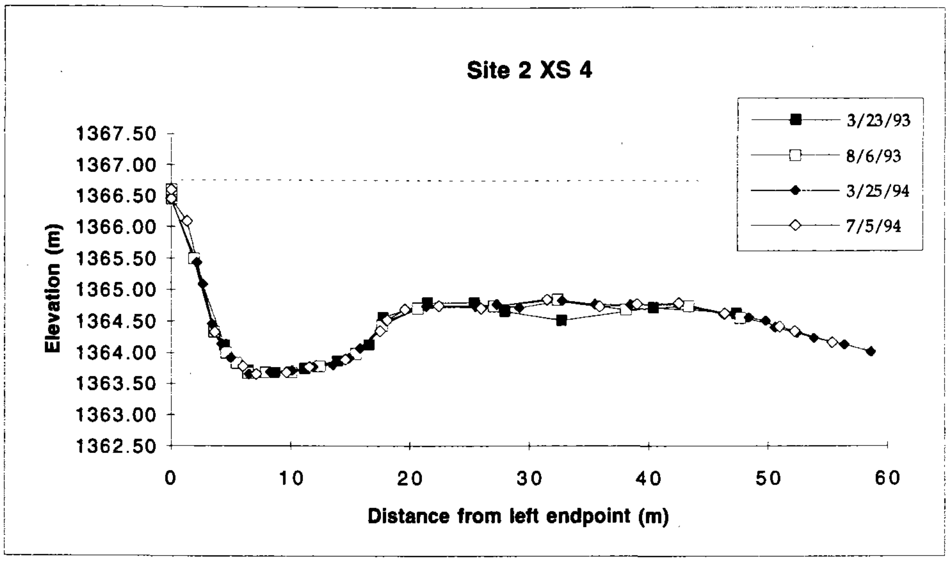


Figure 10. Channel cross-sections of Site 2. Cross-sections 1-4 are at the upstream end, 5-7 are intermediate, and 8-10 are at the downstream end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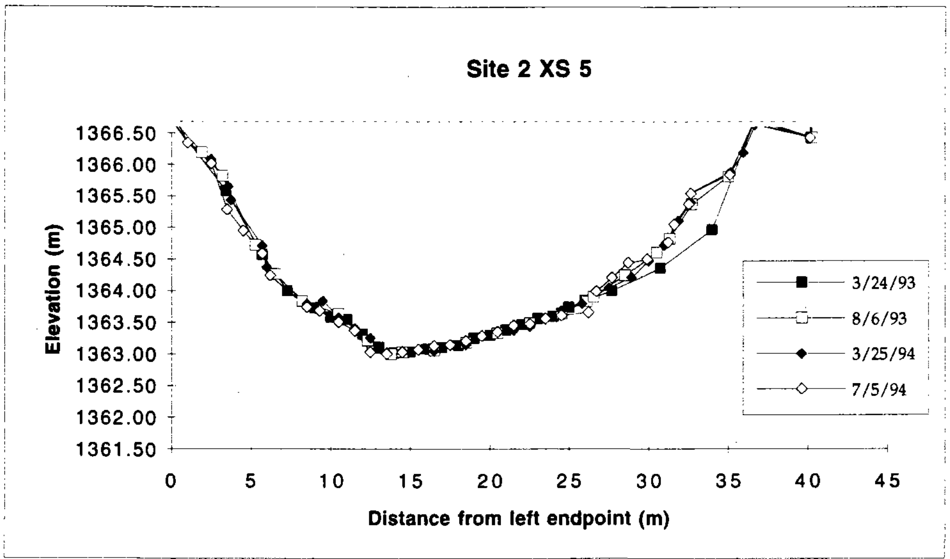
1366.50
1366.00
1365.50
1365.00
1364.50
1364.00
1363.50
1363.00
1362.50
0
10
20
30
40
50
60
Distance from left endpoint (m)
3/23/93
8/6/93
3/25/94
7/5/94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1362.00
1361.50
0
5
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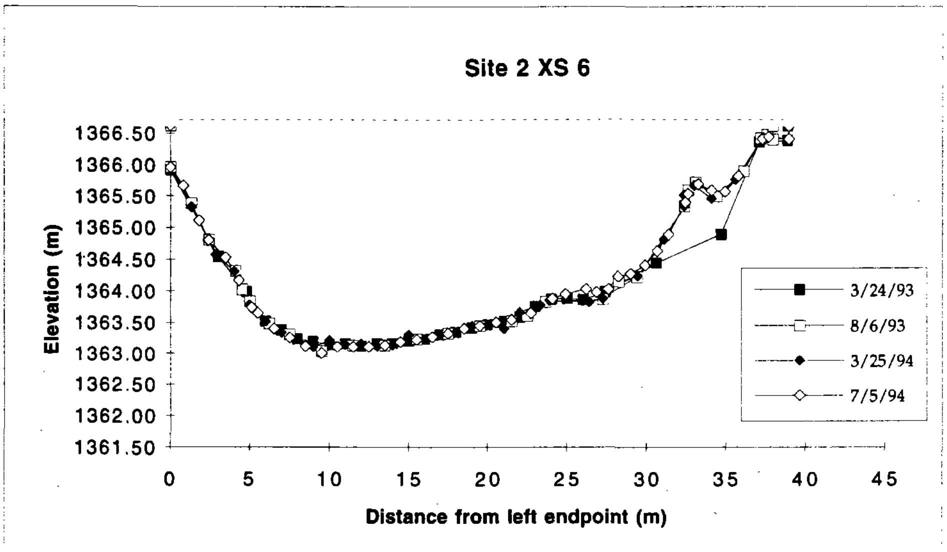
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0
5
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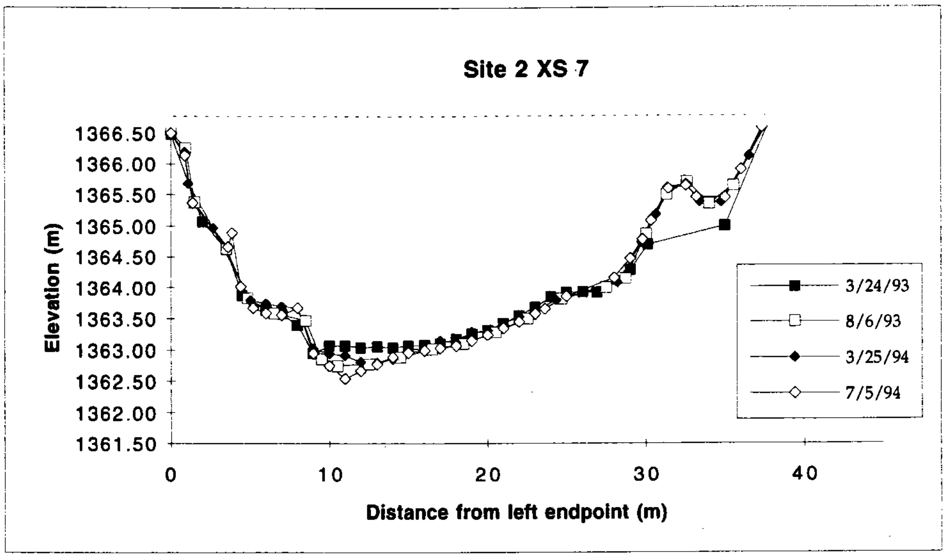
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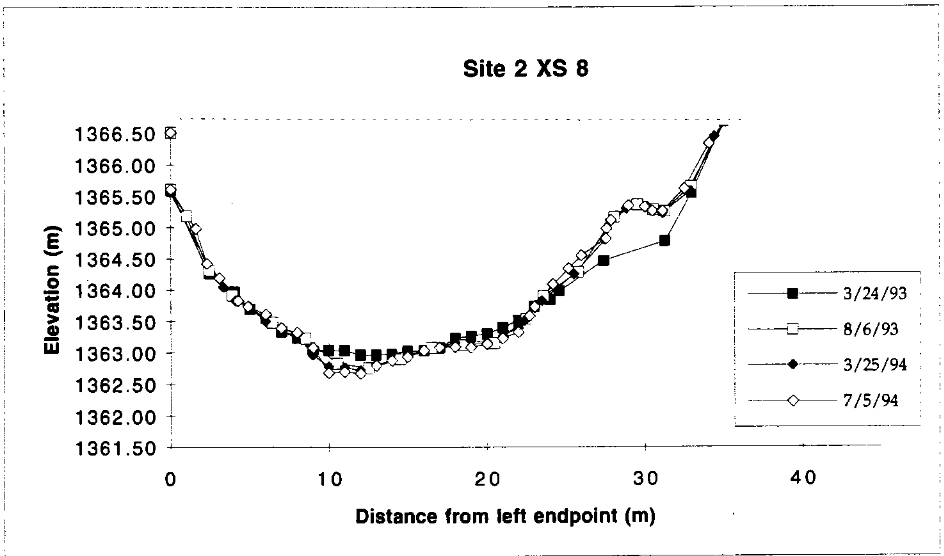
1364.00
1363.50
1363.00
1362.50
1362.00
1361.50
Elevation (m)
0
10
20
30
40
Distance from left endpoint (m)
3/24/93
8/6/93
3/25/94
7/5/94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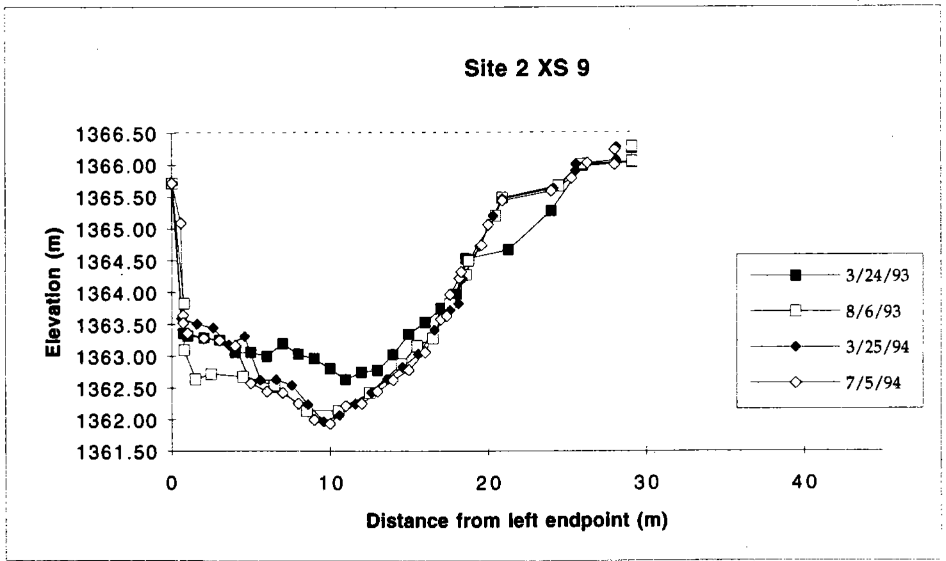
1363.00
1362.50
1362.00
1361.50
Elevation (m)
0
10
20
30
40
Distance from left endpoint (m)
3/24/93
8/6/93
3/25/94
7/5/94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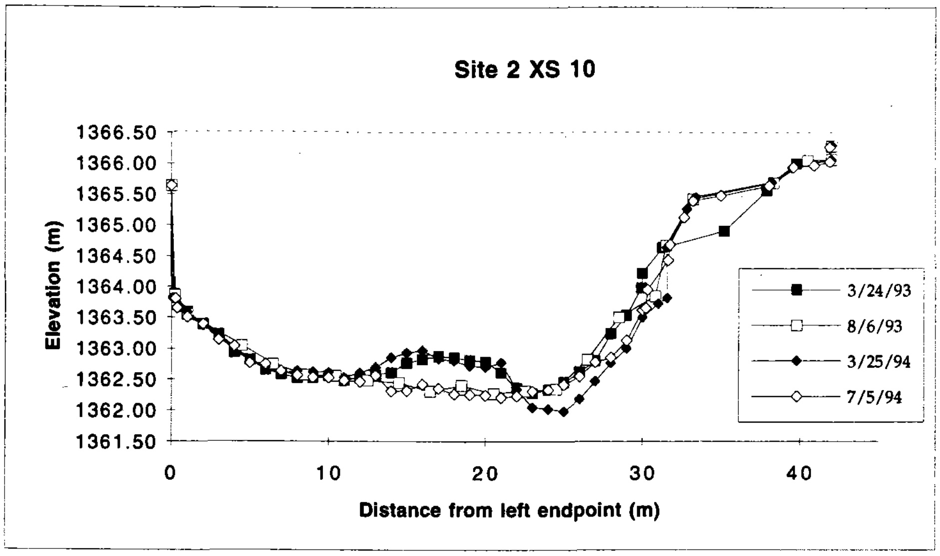
1366.00
1365.50
1365.00
1364.50
1364.00
1363.50
1363.00
1362.50
1362.00
1361.50
Elevation (m)
0
10
20
30
40
Distance from left endpoint (m)
3/24/93
8/6/93
3/25/94
7/5/94


Site 2 XS 10
1366.50
1366.00
1365.50
1365.00
1364.50
1364.00
1363.50
1363.00
1362.50
1362.00
1361.50
Elevation (m)
0
10
20
30
40
Distance from left endpoint (m)
3/24/93
8/6/93
3/25/94
7/5/94

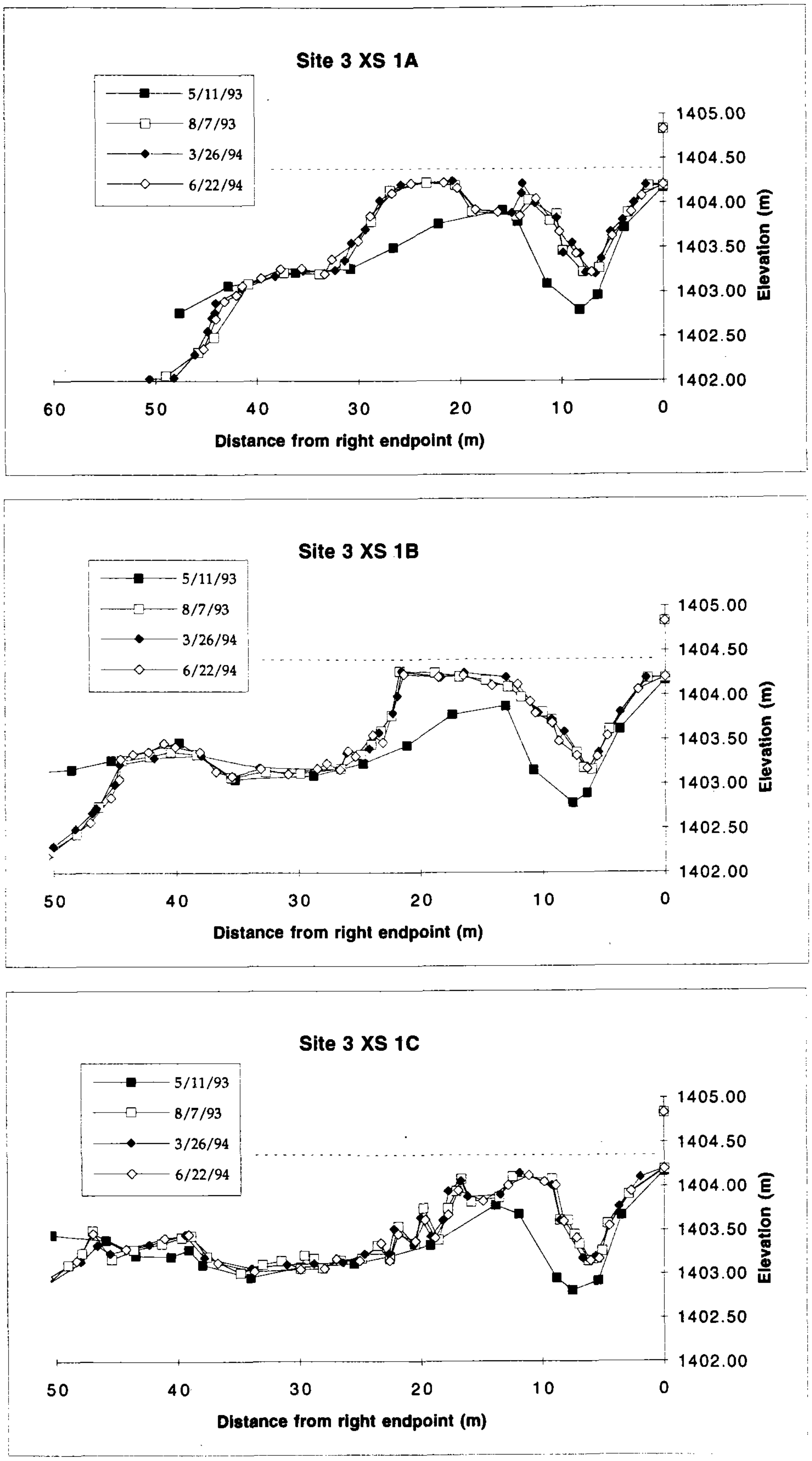
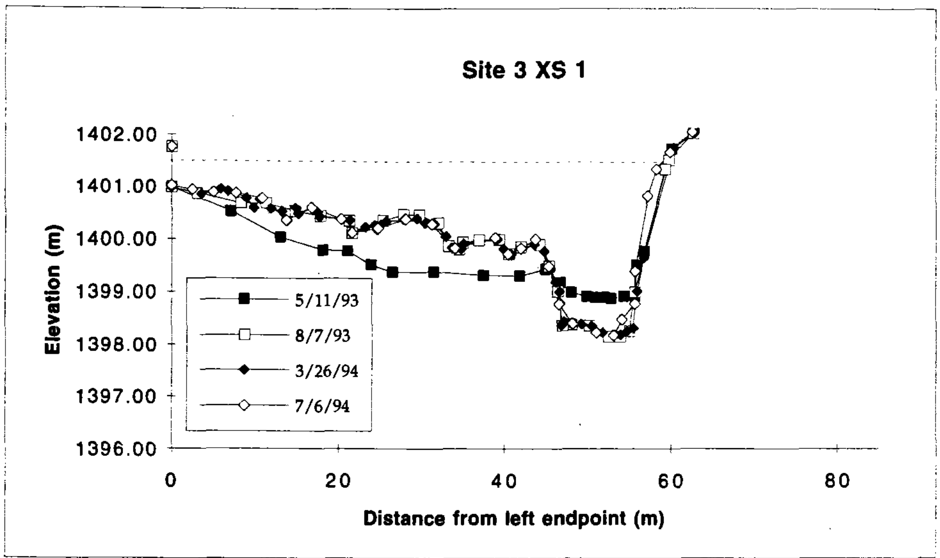
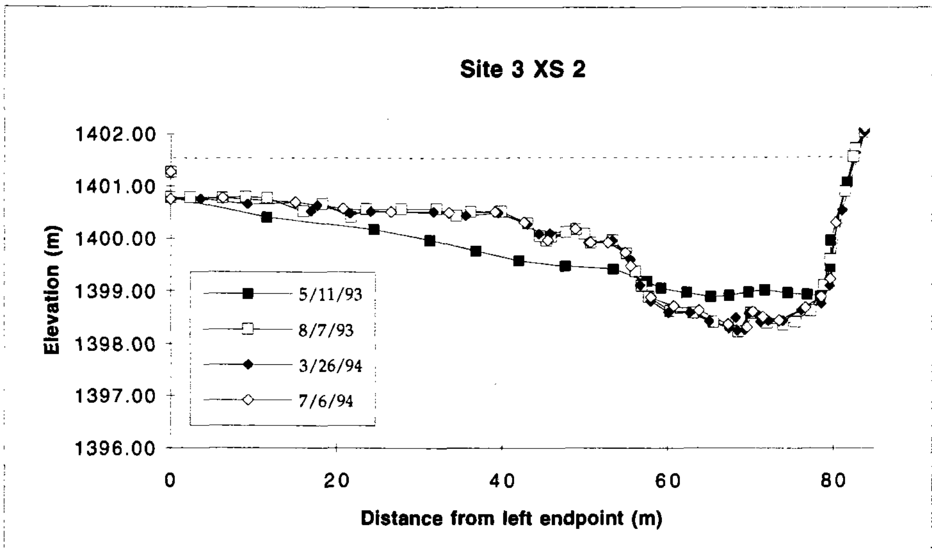


Figure 11. Channel cross-sections of Site 3. Cross-sections 1a-1c are at the upstream end, 1 and 2 are intermediate, and 3-5 are at the downstream end


Site 3 XS 1
1402.00
1401.00
1400.00
1399.00
1398.00
1397.00
1396.00
Elevation (m)
5/11/93
8/7/93
3/26/94
7/6/94
0
20
40
60
80
Distance from left endpoint (m)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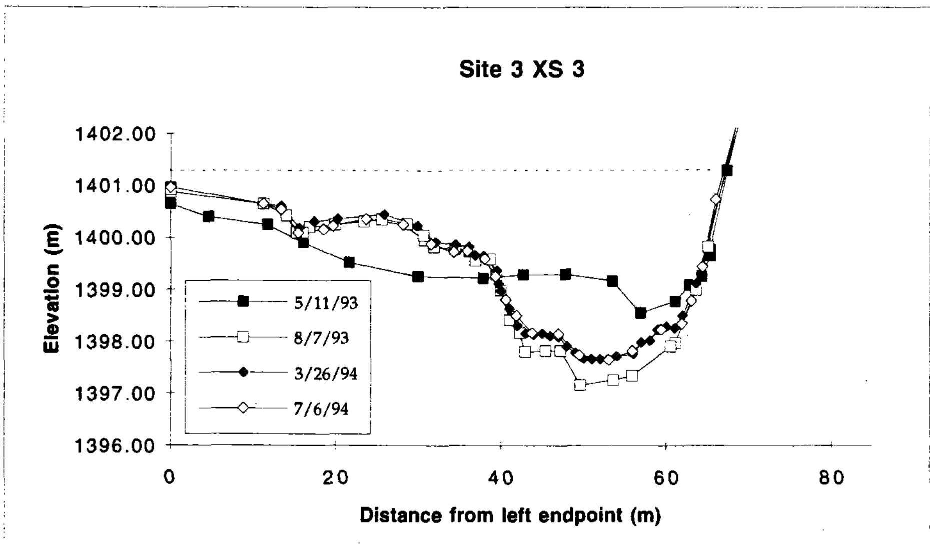
1401.00
1400.00
1399.00
1398.00
1397.00
1396.00
Elevation (m)
5/11/93
8/7/93
3/26/94
7/6/94
0
20
40
60
80
Distance from left endpoint (m)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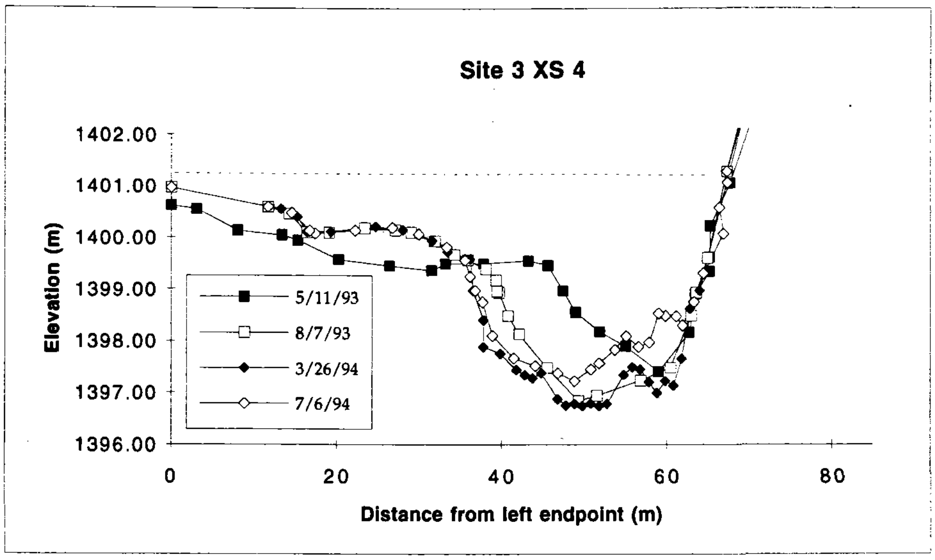
1401.00
1400.00
1399.00
1398.00
1397.00
1396.00
Elevation (m)
5/11/93
8/7/93
3/26/94
7/6/94
0
20
40
60
80
Distance from left endpoint (m)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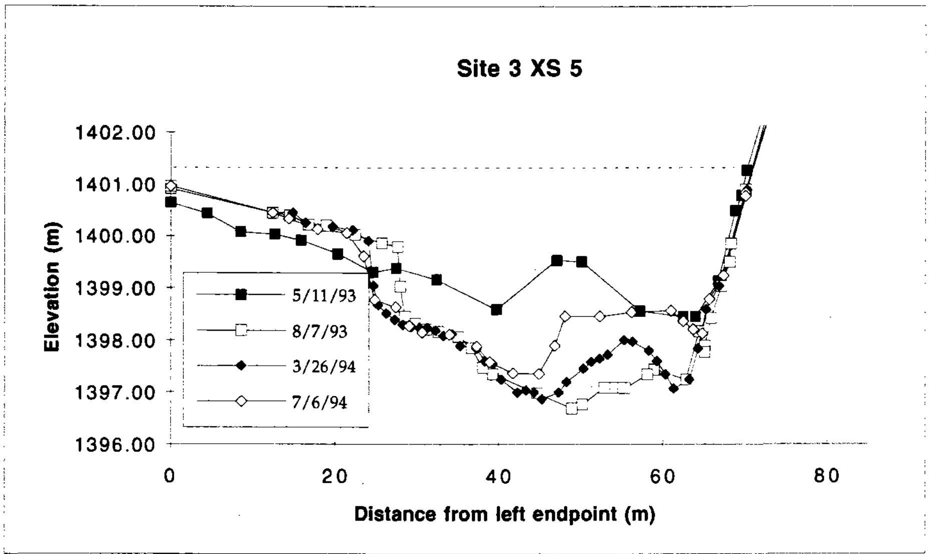
1402.00
1401.00
1400.00
1399.00
1398.00
1397.00
1396.00
Elevation (m)
0
20
40
60
80
Distance from left endpoint (m)
5/11/93
8/7/93
3/26/94
7/6/94


Site 3 XS 5
1402.00
1401.00
1400.00
1399.00
1398.00
1397.00
1396.00
Elevation (m)
0
20
40
60
80
Distance from left endpoint (m)
5/11/93
8/7/93
3/26/94
7/6/94

Although a low flow year like 1994 generally causes only a small amount of deposition at the mouths of these backwaters, it is still unclear how several consecutive low flow year would affect this habitat. If deposition from consecutive low flow years is additive, it is likely that access to these backwaters would become limited.

EVALUATION OF COARSE-SEDIMENT TRANSPORT

The channel of the Colorado River in the Grand Valley and Ruby-Horsethief Canyon is formed by gravel- and cobble-sized sediment. Any future recommendations for habitat improvement for endangered fish will need to consider what flows are required to move the coarse substrate of the upper Colorado River. By definition, complex or multi-thread channel reaches are formed because of bank erosion and bar deposition. For either of these processes to occur, the bed material must be in motion, and thus, it is necessary to define the conditions under which sediment transport is initiated. In natural rivers, this task is complicated by effects associated with the variation in sediment properties and bed topography. We have tried to address some of these complications by selecting a number of different sites and using techniques that account for the spatial variability in bed topography and flow.

In the absence of direct observations of tagged-particle movement or bed-load transport, the only practical means for estimating the threshold for sediment transport (or critical shear stress, τ_c) is to use an empirical relation. The most common approach is to use Shields' parameter

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)\, g\, D} \qquad (1)$$

where τ^*_c is the critical dimensionless shear (Shields) stress, ρ_s and ρ are the density of sediment and water respectively, g is the gravitational acceleration, and D is the particle diameter. According to eqn. 1, a particle begins to move when the critical value of τ^*_c is exceeded (or equivalently when the available shear stress, τ, exceeds the critical shear stress, τ_c). In rivers with poorly sorted sediment, i.e. sizes ranging from sand to gravel, the value of τ^*_c has been shown to vary from < 0.01 to > 0.2 depending on whether particles are larger or smaller than the median grain size, D_{50} (Komar, 1987; Andrews, 1983). As it turns out, however, larger particles tend to be more exposed to the flow while smaller particles tend to be hidden in pockets, and thus most particles will begin to move at nearly the same shear stress (Wilcock and Southard, 1988; Andrews, 1983; Parker et al., 1982). Under this assumption, a single value of Shields parameter corresponding to a particular grain size (e.g. D_{50}) can be used to determine the threshold for motion. For D_{50}, a value of τ^*_c = 0.03 is commonly used as the criterion for *initial* motion. At this level of shear stress, sediment transport is very weak, involving the sporadic movement of just a few particles. As the flow and shear stress increase, more and more particles become entrained, until at a value of about $\tau^*_c = 0.06$, there is *significant* motion and almost all particles on the bed will be moving.

To evaluate when the critical shear stress is reached, we must determine the range in shear stress for different flows. The average boundary shear stress can be defined by the equation

$$\tau = \rho g h s_f \qquad (2)$$

where h is the flow depth, and s_f is the friction slope, or streamwise energy gradient. Over very long reaches (> 1km), s_f can be approximated by the bed or water-surface slope, but over shorter reaches (e.g. one pool-riffle-run sequence), s_f must be calculated from a step-wise solution to the 1-dimensional momentum equation

$$s_f = s_o - \frac{u}{g}\frac{\partial u}{\partial x} - \frac{\partial h}{\partial x} - \frac{1}{g}\frac{\partial u}{\partial t} \qquad (3)$$

where *u* is the mean velocity, *x* is the streamwise direction, and *t* is time. For flows that do not vary with time or vary slowly with time (steady flow), $\partial u/\partial t = 0$, hence the right-hand term in (3) can be eliminated. Peak spring and summer flows in the upper Colorado River are derived from snowmelt higher in the basin and the discharge does not change rapidly from one day to the next- the snowmelt hydrograph typically lasts for several months- and thus, for time steps of one day or so, it is reasonable to assume that the discharge is steady. Equation (3) can be solved iteratively for a series of cross sections where the bed slope, flow depth and velocity are known (Henderson, 1966; Dingman, 1984).

Study Sites and Methods

The field sites for this analysis are located near the Palisade gauge (~RM 184.2), near the Corn Lake boat launch (~RM 177.3), below the Redlands Parkway bridge (~RM 166), approximately half way between the Redlands Parkway and Fruita bridges (~RM 162.4) and at both the old (~RM 139.5) and new (~RM 134) sites of the USGS State-line gauge (Fig. 1). All of these sites are in single thread, relatively straight reaches of the river. Six or seven cross-sections were surveyed at each site during the spring and summer of 1994 by the method described previously (Figures 12 through 17). The cross-sections were placed approximately one channel width apart. Water surface elevations at each cross-section were measured at several flows throughout the runoff season, and the elevation of the 1993 peak flow was estimated from high water marks. These measurements provide us with important information on both the depth and slope at each cross-section which is essential to an accurate calculation of the boundary shear stress.

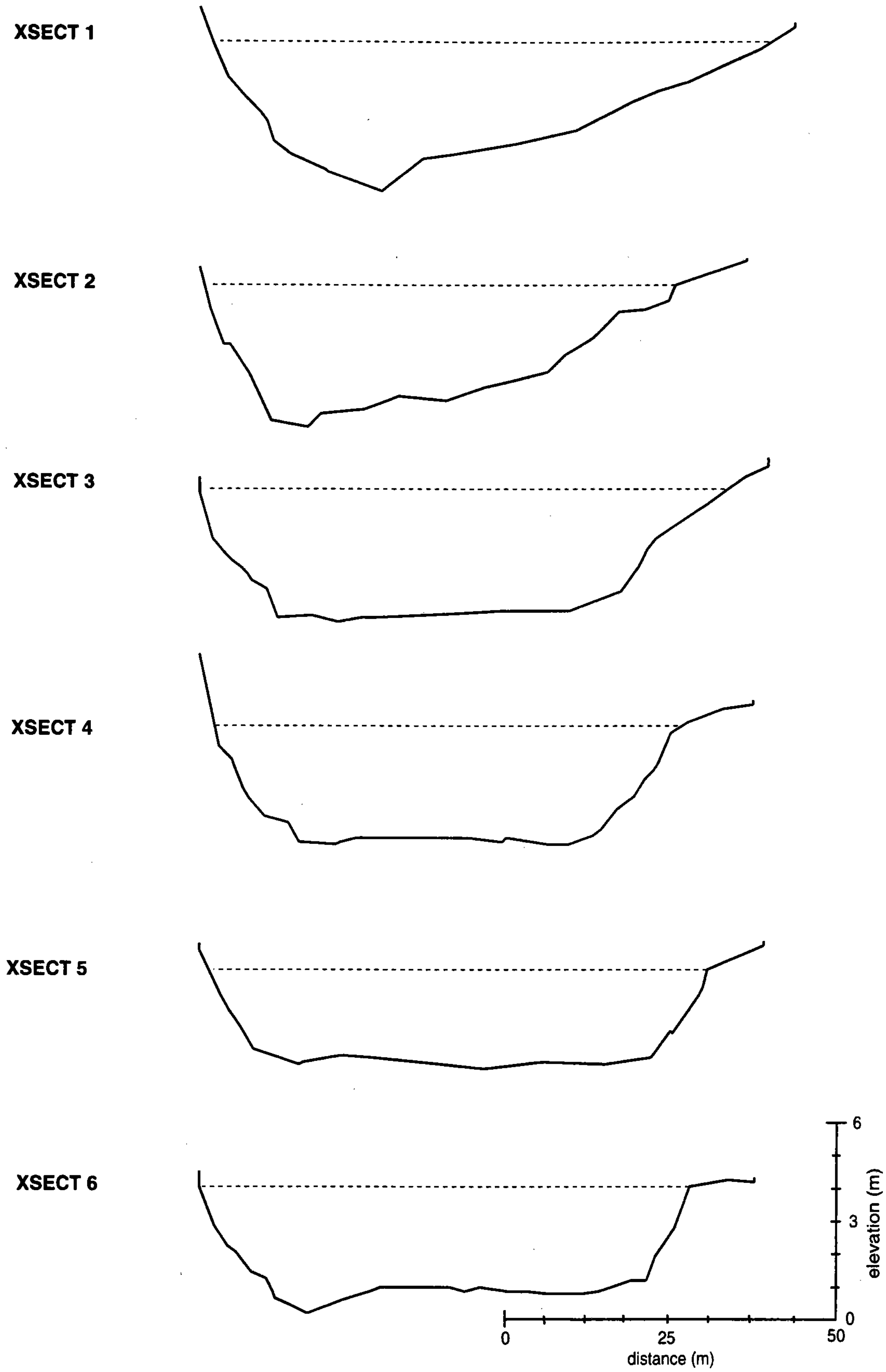


Figure 12. Main channel cross-sections of the Palisade site

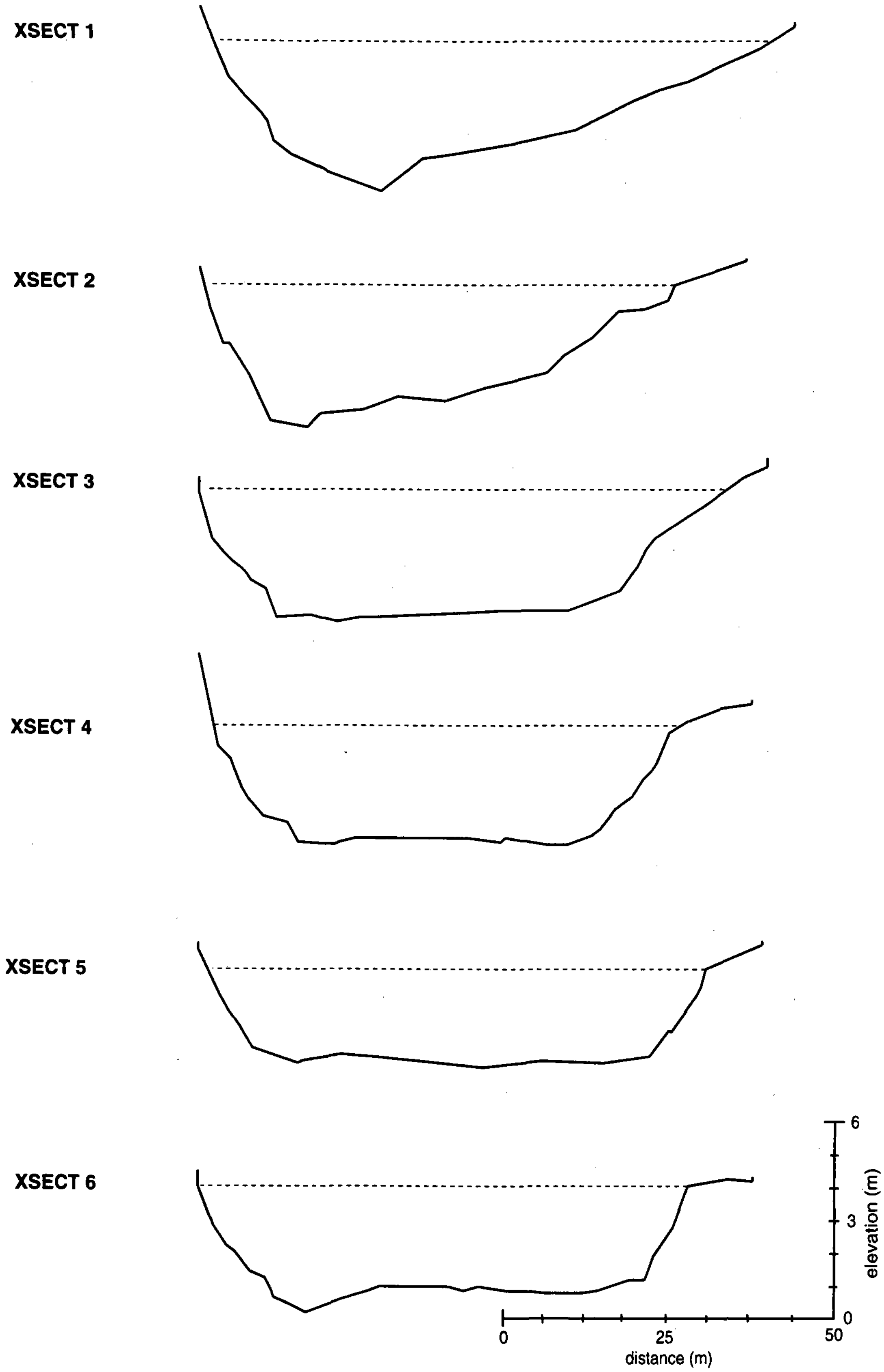


Figure 13. Main channel cross-sections of the Corn Lake site

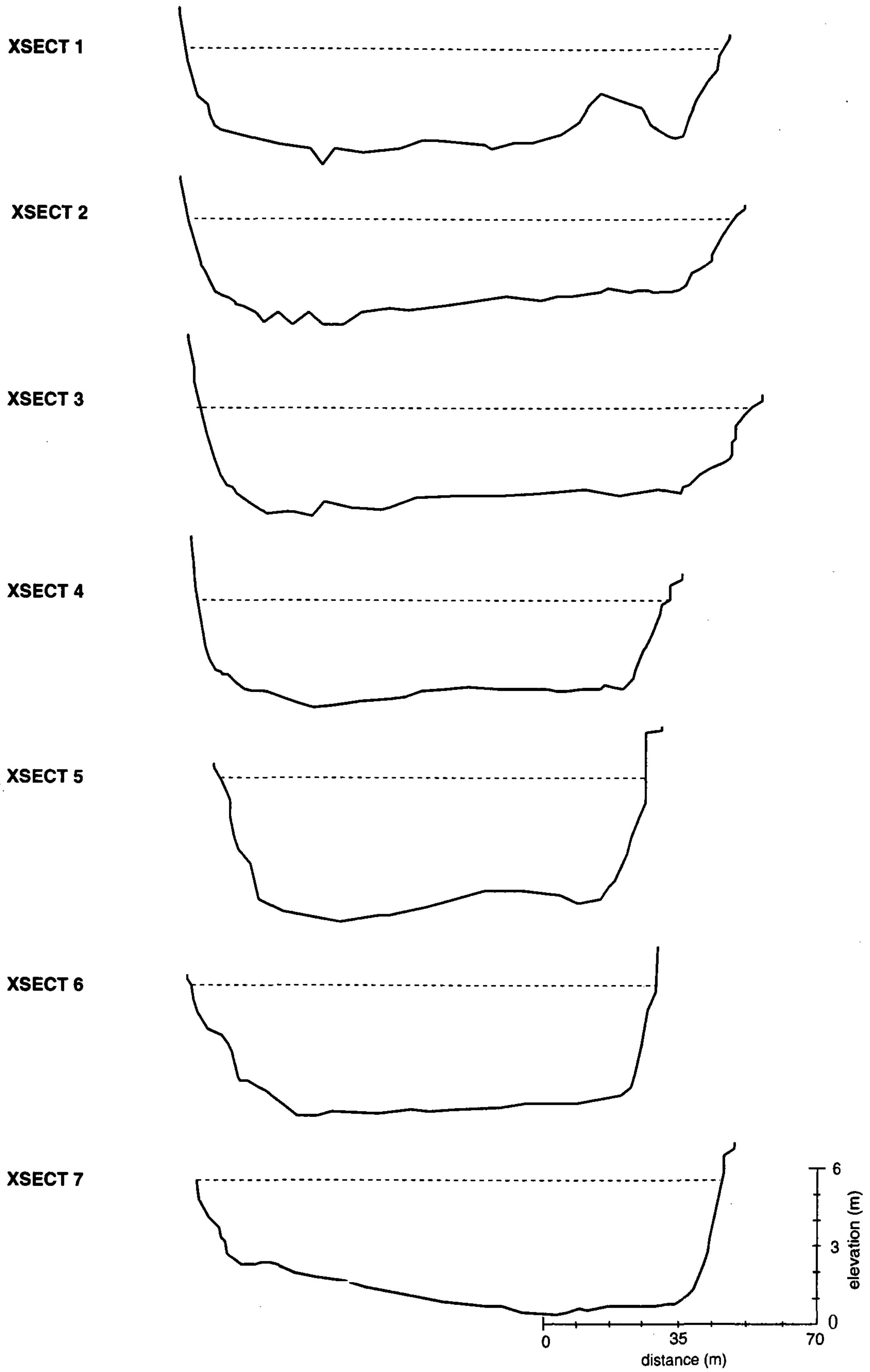


Figure 14. Main channel cross-sections of the Redlands Parkway site

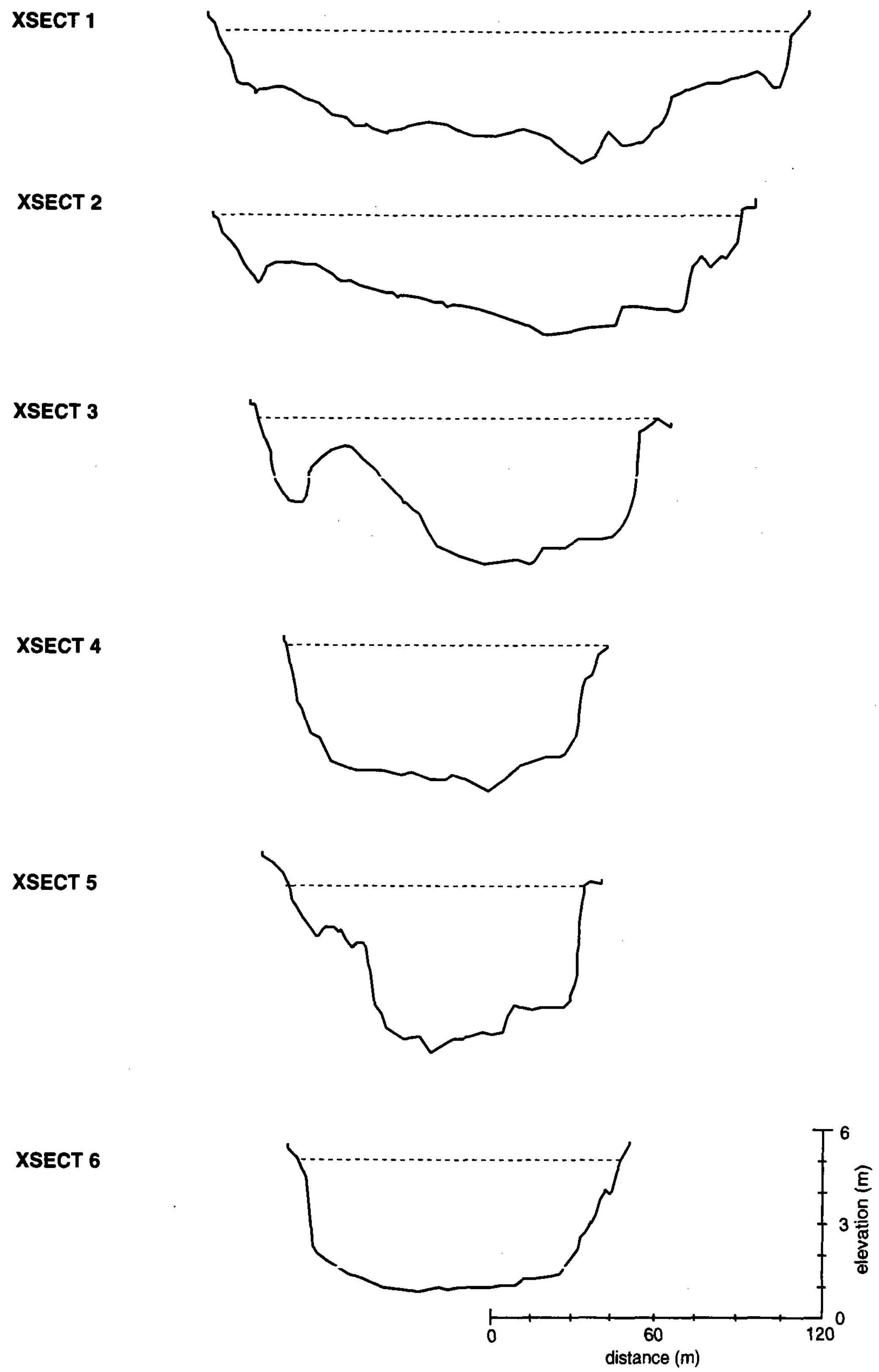


Figure 15. Main channel cross-sections of site RM 162.4

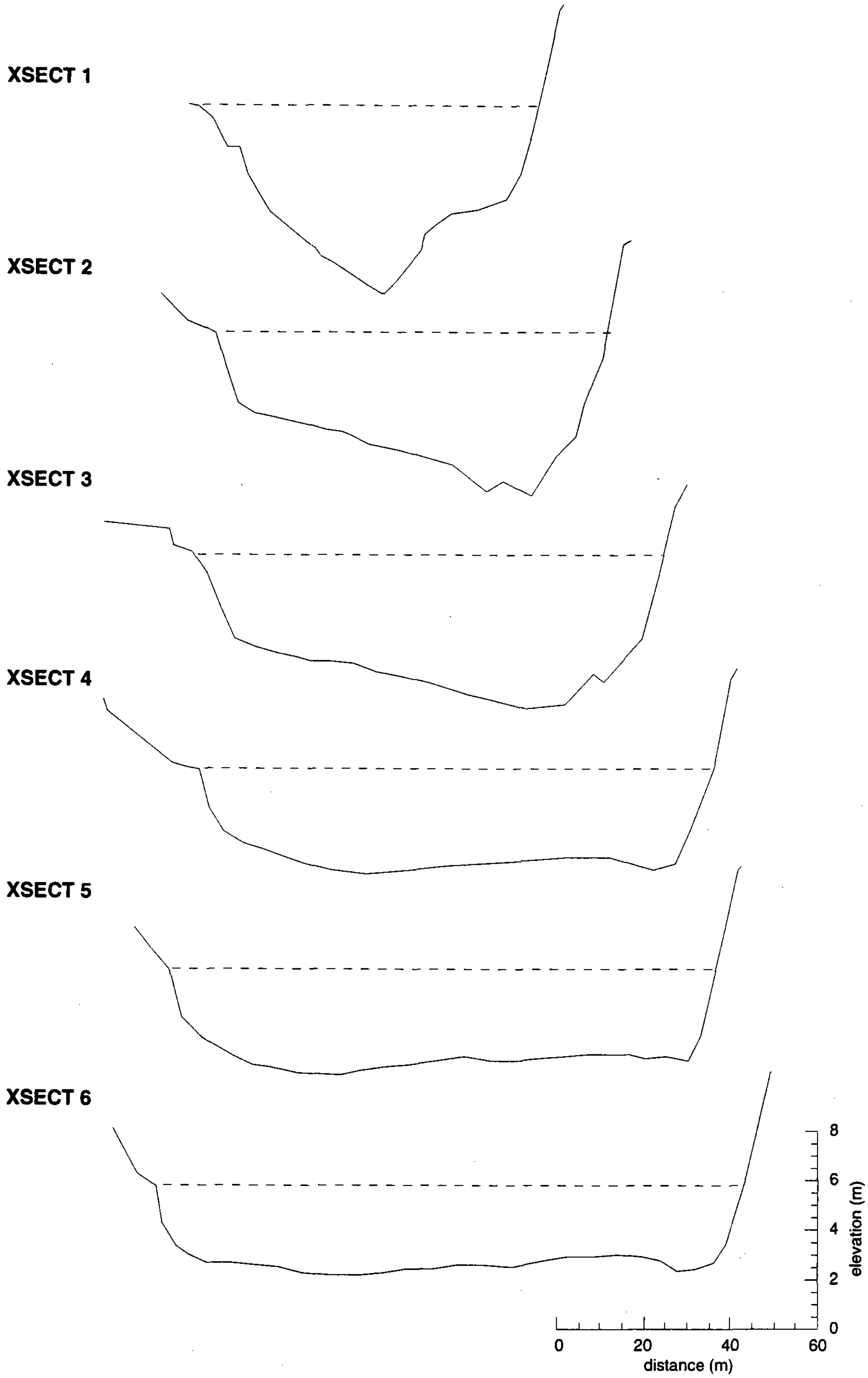


Figure 16. Main channel cross-sections of the Old Gauge site

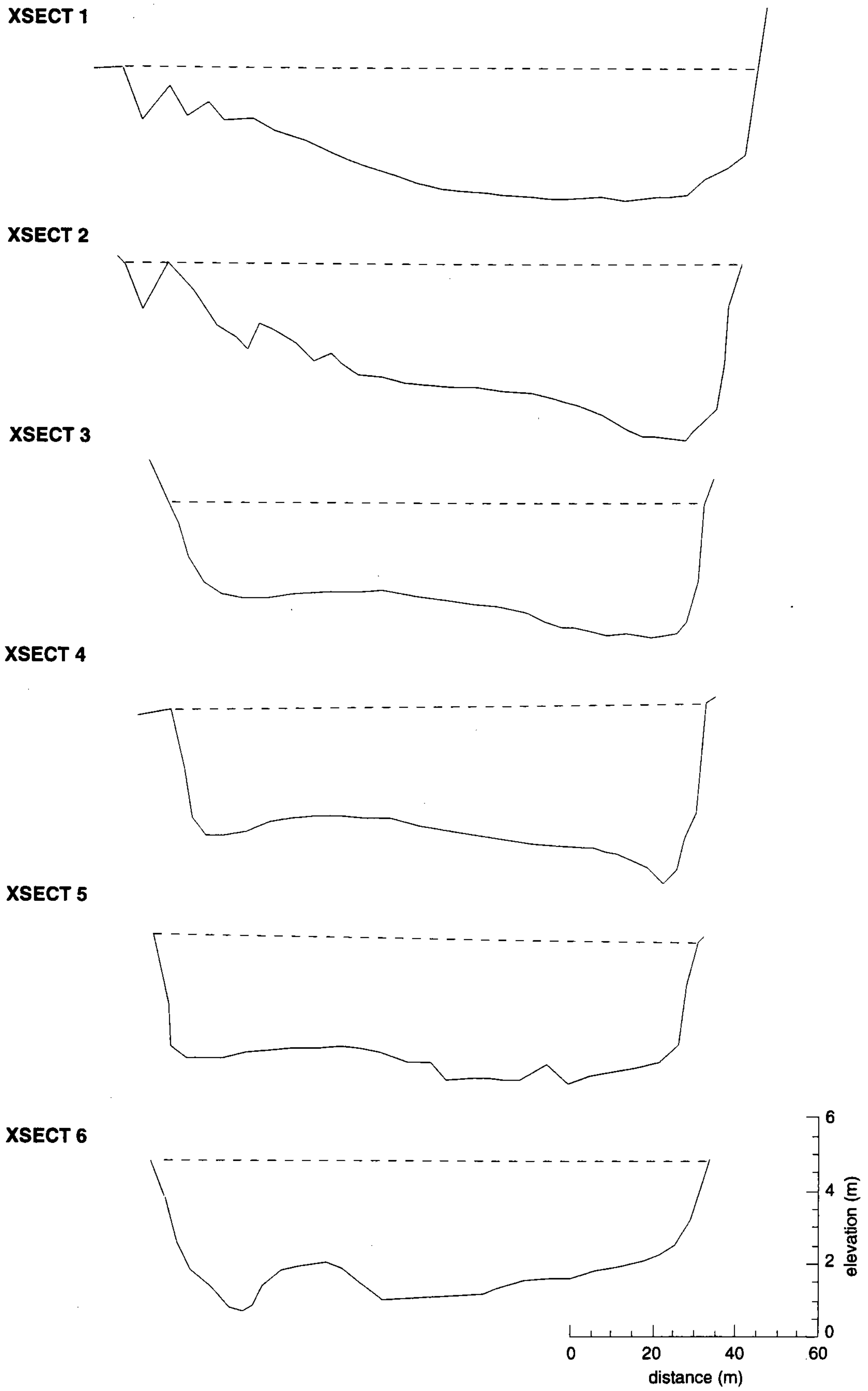


Figure 17. Main channel cross-sections of the New Gauge site

Results

Palisade

Flows at the Palisade site show an increase in the reach averaged velocity, depth, slope, and shear stress with increasing discharge (Table 5). Figure 18 shows how the bed elevation, and water surface slope change at different flows. At a flow of 54 cms the slope is relatively flat since there is a riffle downstream of the surveyed cross-sections which backs up the flow. At higher discharges this downstream control has a smaller affect and the slope increases at all cross-sections, but especially over the crest of the riffle. Figure 18 also illustrates the relationship between shear stress and discharge. It shows that initial motion ($\tau^*=0.03$) of D_{50} occurs near a discharge of 350 cms (12,350 cfs) and significant transport associated with $\tau^*=0.06$ occurs at a discharge near 725 cms (25,600 cfs). These flows are approximately the 1.26 and 4.3 year flood respectively.

Corn Lake

Flows at Corn Lake show a similar trend to Palisade with an increase in reach averaged velocity, depth, slope, and shear stress with increasing discharge (Table 6). Figure 19 shows that the water surface is relatively flat at low flows, but the slope increases with discharge. It also shows that initial motion of D_{50} occurs near a discharge of 250 cms (8,825 cfs), and significant transport occurs at a discharge of approximately 525 cms (18,525 cfs). These flows are approximately the 1.11 and 2.0 year flood respectively. These values are less than those at Palisade primarily because the grain size is finer at Corn Lake.

Table 5. Summary of Hydraulic Data (Palisade)

discharge = 54 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.34	0.68	0.0004	0.004	5.0
2	1.67	0.56	0.0002	0.003	3.2
3	0.97	0.75	0.0007	0.006	6.9
4	0.87	0.84	0.0010	0.007	8.9
5	0.95	0.80	0.0008	0.006	7.8
6	1.19	0.58	0.0003	0.003	3.8
reach average:	1.17	0.70	0.0006	0.005	5.9

discharge = 252 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	2.25	1.74	0.0012	0.021	25.5
2	2.46	1.62	0.0009	0.018	21.7
3	1.82	1.76	0.0016	0.023	28.2
4	1.55	1.89	0.0022	0.028	34.0
5	1.51	2.01	0.0026	0.032	38.9
6	1.81	1.68	0.0014	0.021	25.7
reach average:	1.90	1.78	0.0017	0.024	29.0

discharge = 712 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	3.29	2.96	0.0019	0.051	62.3
2	3.32	2.98	0.0019	0.052	62.8
3	2.79	2.87	0.0023	0.051	61.9
4	2.64	2.92	0.0025	0.054	65.2
5	2.47	3.23	0.0034	0.067	81.7
6	2.75	3.02	0.0025	0.057	68.6
reach average:	2.89	3.00	0.0024	0.055	67.06

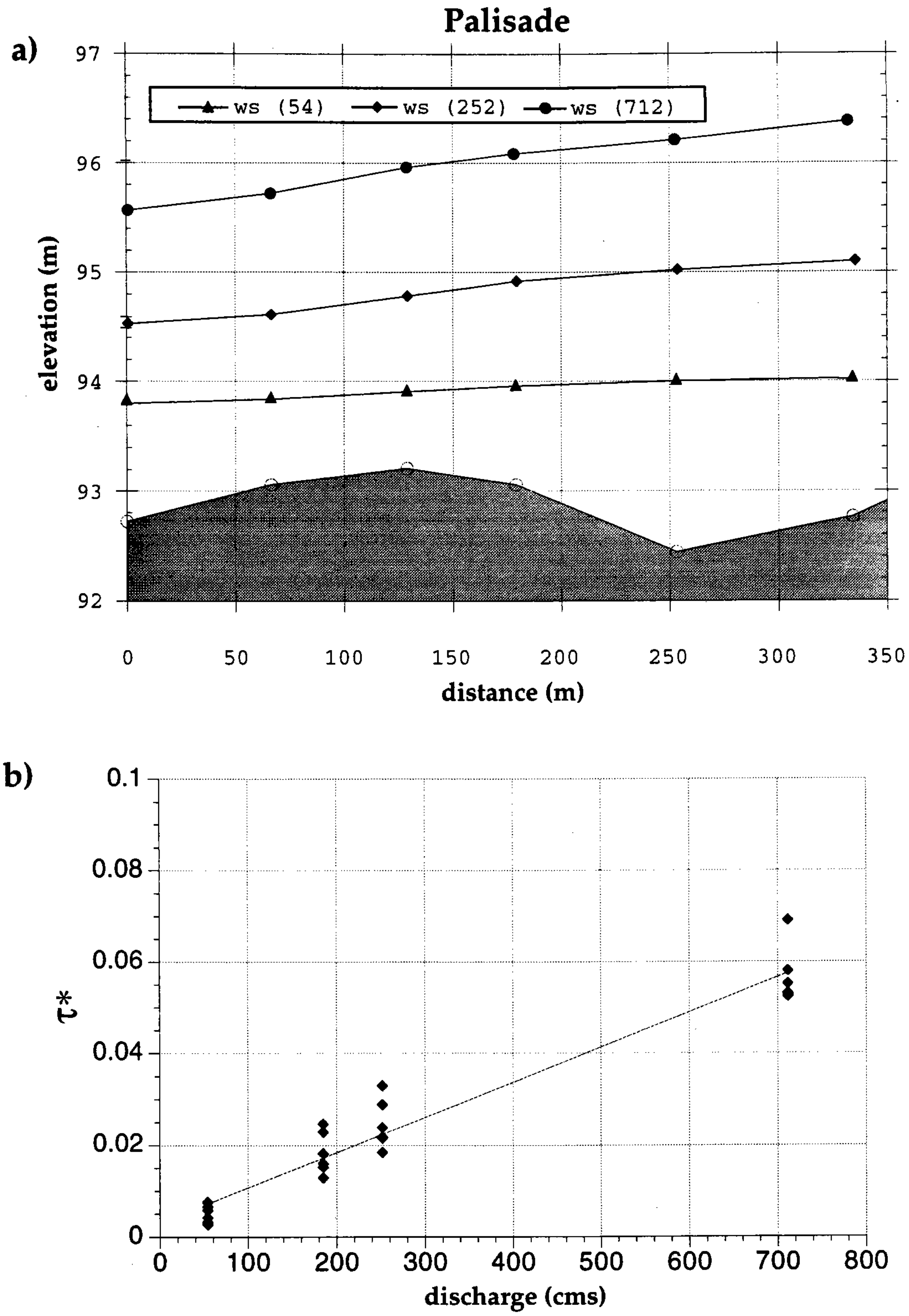


Figure 18. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at the Palisade site

Table 6. Summary of Hydraulic Data (Corn Lake)

discharge = 54 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.13	0.79	0.0006	0.009	7.0
2	1.57	0.57	0.0002	0.004	3.3
3	1.45	0.64	0.0003	0.005	4.1
4	1.42	0.69	0.0004	0.006	4.9
5	1.23	0.70	0.0004	0.007	5.2
6	1.35	0.66	0.0003	0.006	4.5
reach average:	1.36	0.68	0.0004	0.006	4.84

discharge = 185 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.92	1.58	0.0012	0.028	22.1
2	2.47	1.37	0.0006	0.020	15.2
3	2.11	1.44	0.0009	0.023	17.9
4	2.01	1.59	0.0011	0.028	22.0
5	1.79	1.56	0.0012	0.028	22.0
6	1.82	1.56	0.0012	0.028	22.0
reach average:	2.02	1.51	0.0010	0.026	20.2

discharge = 712 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	3.31	2.72	0.0016	0.067	51.9
2	3.49	2.69	0.0014	0.064	49.6
3	3.39	2.81	0.0017	0.071	55.0
4	3.28	3.27	0.0023	0.097	75.0
5	2.99	3.03	0.0023	0.086	66.6
6	2.89	3.28	0.0028	0.102	79.0
reach average:	3.23	2.97	0.0020	0.081	62.9

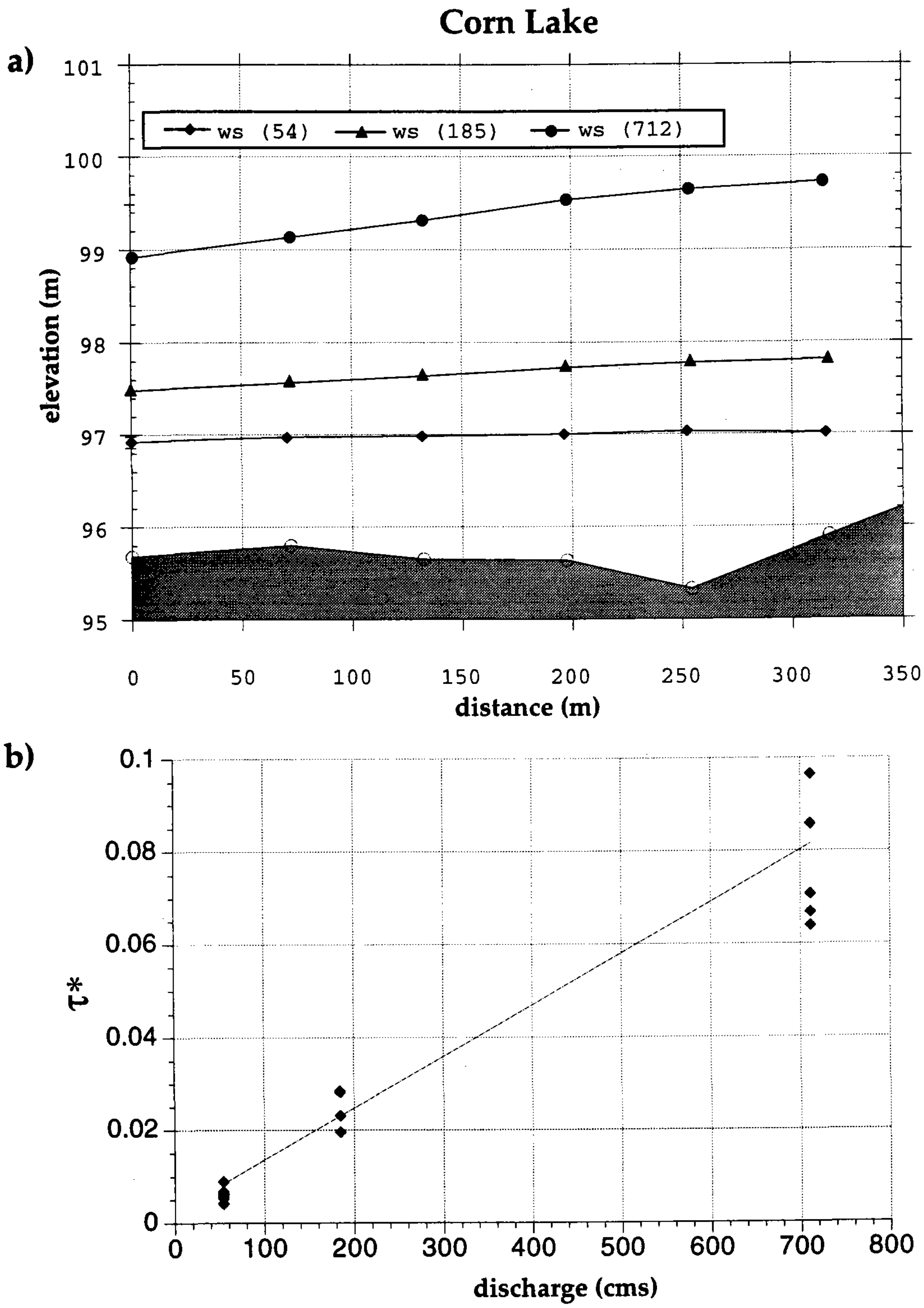


Figure 19. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at the Corn Lake site

Redlands Parkway

The hydraulic characteristics of the Redlands Parkway site are slightly different from the others (Table 7). The reach averaged slope is steeper at low flow than at moderate flow due to a riffle at the upstream end of the site. Although the slope decreases at moderate flows, the shear stress increases because of the greater water depth. The highest flows yield the greatest reach averaged slope, depth, velocity, and shear stress, as at the other sites. Figure 20 shows that the flow accelerates over the riffle at the upstream end of the site at all discharges, and the slope becomes relatively flat at the downstream end at low flows due to the ponding effects of a downstream riffle. At high flows, this riffle is drowned out and the slope remains relatively steep at the downstream end. It also shows that initial motion of D_{50} occurs at a discharge of approximately 420 cms (14,825 cfs) and significant motion occurs near 1100 cms (38,825 cfs). These are approximately the 1.81 and 4.0 year flood respectively.

RM 162.4

This site is similar to the others in illustrating a general increase in reach averaged velocity, depth, slope, and shear stress with discharge (Table 8). Figure 21 shows that the flow mimics the bed topography at low flow, but at higher flow the topographic features are drowned out and the slope becomes more uniform. It also shows that initial motion of bed material occurs near a discharge of 575 cms (20,300 cfs) and significant motion at flows near 1300 cms (46,000 cfs). This is approximately the 1.42 and 6.5 year flood respectively. Although the grain size is similar, the slope of this site is less than that at the Redlands Parkway site, therefore a larger discharge is needed in order to result in a similar boundary shear stress.

Table 7. Summary of Hydraulic Data (Redlands Parkway)

discharge = 135 m^3/s

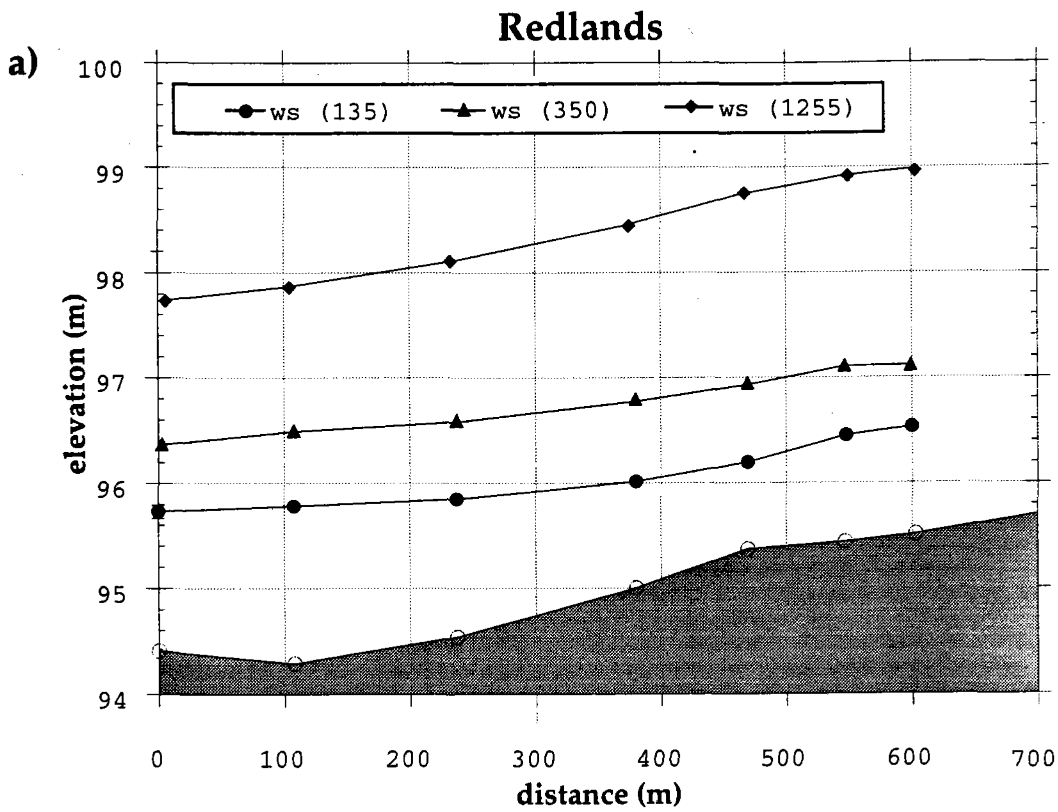
xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.08	1.30	0.0018	0.020	18.9
2	1.04	1.36	0.0021	0.023	21.1
3	0.92	1.52	0.0030	0.030	27.4
4	1.08	1.29	0.0018	0.020	18.6
5	1.37	1.11	0.0010	0.014	12.8
6	1.53	0.87	0.0005	0.008	7.6
7	1.35	0.82	0.0005	0.008	7.0
reach average:	1.20	1.18	0.0015	0.018	16.2

discharge = 350 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.60	1.72	0.0017	0.029	26.7
2	1.67	1.76	0.0017	0.030	27.5
3	1.58	1.85	0.0020	0.034	30.9
4	1.80	1.80	0.0016	0.030	27.9
5	2.06	1.79	0.0013	0.028	26.3
6	2.21	1.52	0.0009	0.020	18.6
7	2.02	1.39	0.0008	0.017	16.0
reach average:	1.85	1.69	0.0014	0.027	24.8

discharge = 1255 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	3.33	2.79	0.0016	0.055	51.1
2	3.29	2.74	0.0015	0.054	49.5
3	3.21	2.89	0.0017	0.059	54.9
4	3.33	3.15	0.0020	0.071	65.3
5	3.21	3.66	0.0028	0.096	89.0
6	3.29	3.25	0.0022	0.076	69.7
7	3.20	2.99	0.0019	0.064	59.3
reach average:	3.27	3.07	0.0020	0.068	62.7



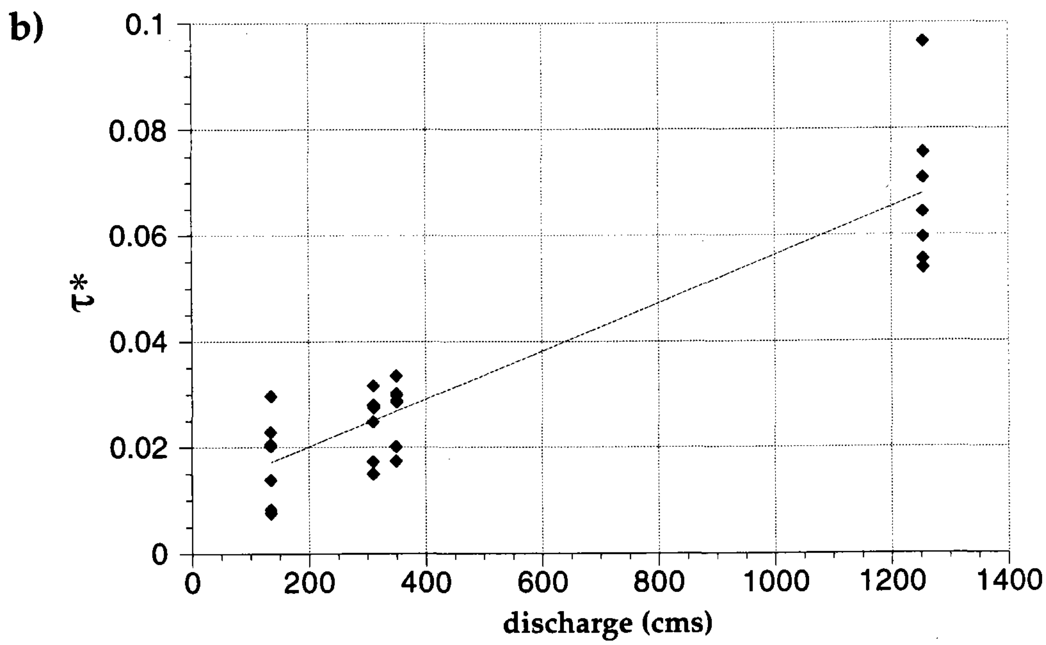


Figure 20. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at the Redlands Parkway site

Table 8. Summary of Hydraulic Data (RM 162.4 site))

discharge = 135 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	0.83	1.45	0.0032	0.029	25.8
2	0.99	1.24	0.0018	0.020	17.6
3	1.97	0.77	0.0003	0.006	5.4
4	2.49	0.65	0.0001	0.004	3.5
5	2.06	0.65	0.0002	0.004	3.8
6	2.15	0.60	0.0001	0.004	3.2
reach average:	1.75	0.89	0.0010	0.011	9.9

discharge = 575 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	1.54	1.84	0.0021	0.035	31.2
2	1.67	1.85	0.0019	0.035	31.0
3	2.29	1.85	0.0012	0.031	27.8
4	2.97	1.86	0.0009	0.029	25.7
5	2.80	1.87	0.0010	0.030	26.5
6	2.78	1.84	0.0009	0.029	25.7
reach average:	2.34	1.85	0.0013	0.031	28.0

discharge = 1255 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	2.83	2.23	0.0013	0.041	36.6
2	2.92	2.31	0.0014	0.044	38.8
3	3.31	2.60	0.0015	0.053	47.2
4	3.80	2.91	0.0015	0.063	56.4
5	3.68	2.93	0.0016	0.065	58.2
6	3.64	2.92	0.0016	0.065	57.8
reach average:	3.36	2.65	0.0015	0.055	49.2

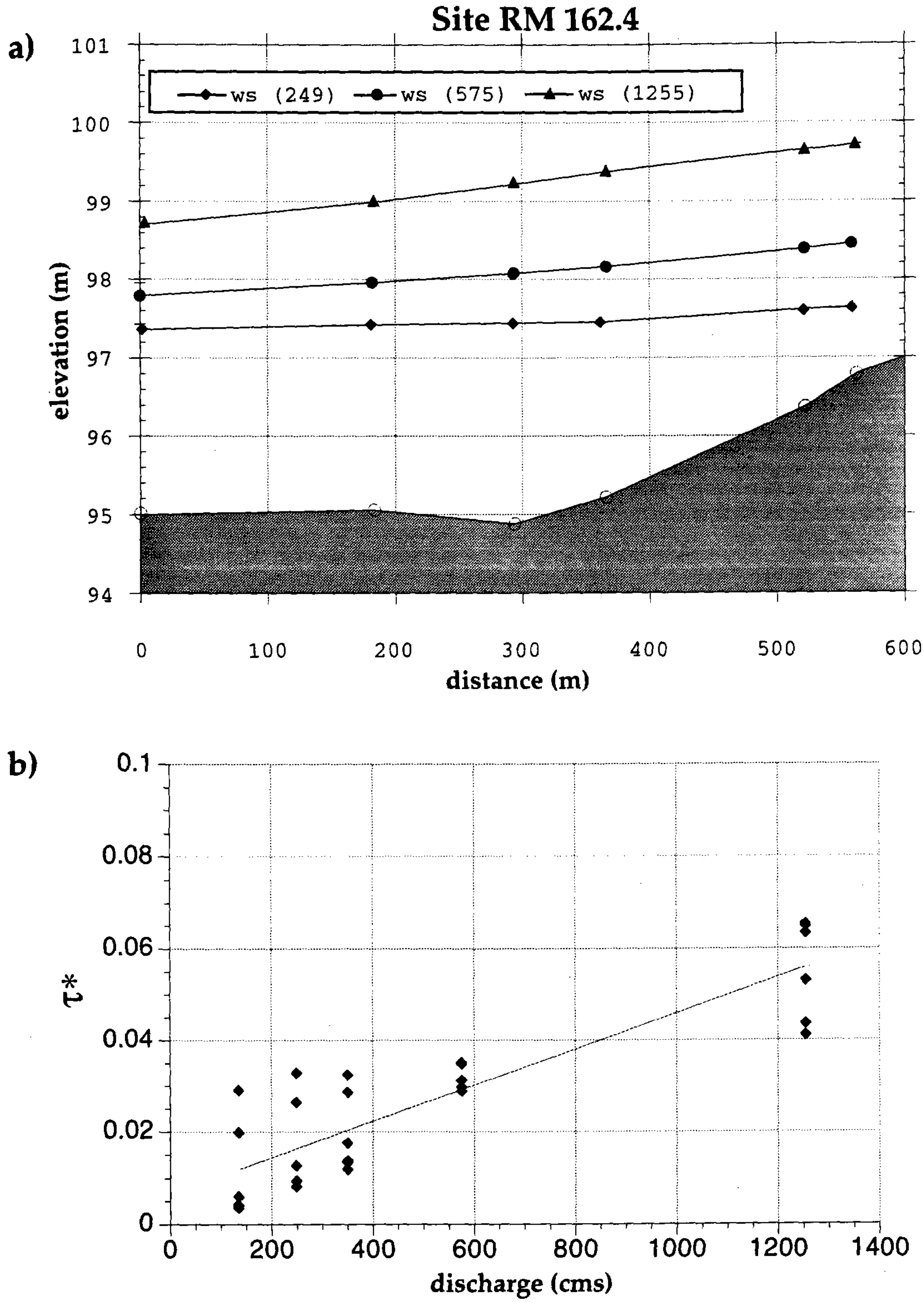


Figure 21. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at site RM 162.4

Old Gauge

This site shows a general increase in reach averaged velocity, depth, slope, and shear stress with discharge (Table 9). Figure 22 shows that at low discharge the flow accelerates over a riffle at the downstream end of the site. As the discharge increases, the discrepancy of velocity between cross-sections evens out as the bed topography becomes drowned out and the water surface slope becomes more uniform. The discharge for initial motion of the bed material occurs near 525 cms (18,500 cfs) and significant motion occurs near 1,050 cms (37,000 cfs) (Fig. 22). These are approximately the 1.42 and 5.5 year flood respectively.

New Gauge

At this site the reach averaged slope is steeper at low flow than at moderate to high flows due to a riffle at the downstream end of the site. Overall, however, the shear stress increases with discharge due to an increase in depth (Table 10). Figure 23 illustrates how the water surface slope mimics the bed topography at low flows, but again becomes more uniform as discharge increases. The average slope is steeper at this site than at the old gauge site, so there is a higher shear stress for a given flow. Initial motion of bed material occurs at a discharge near 275 cms (9,700 cfs), and significant motion occurs at 875 cms (30,900 cfs) (Fig. 23). These flows have return periods of 1.02 and 2.9 years respectively.

Table 9. Summary of Hydraulic Data (USGS Gage, Old Site)

discharge = 77 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	2.57	0.48	0.0001	0.002	1.8
2	1.91	0.51	0.0001	0.003	2.2
3	1.54	0.53	0.0002	0.003	2.6
4	1.13	0.63	0.0004	0.005	4.1
5	1.00	0.67	0.0005	0.006	4.8
6	0.80	0.76	0.0008	0.008	6.6
reach average	1.49	0.60	0.0003	0.005	3.7

discharge = 538 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	4.24	1.98	0.0006	0.030	24.3
2	3.52	1.88	0.0007	0.029	23.4
3	3.08	1.84	0.0008	0.029	23.2
4	2.58	1.92	0.0011	0.033	26.9
5	2.35	1.95	0.0012	0.036	28.8
6	2.00	2.12	0.0018	0.044	35.7
reach average	2.96	1.95	0.0010	0.033	27.1

discharge = 1255 m^3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	5.57	3.37	0.0012	0.079	64.3
2	4.86	3.11	0.0012	0.071	57.3
3	4.41	2.92	0.0012	0.064	52.1
4	3.89	2.88	0.0014	0.065	53.0
5	3.63	2.89	0.0015	0.067	54.6
6	3.25	2.98	0.0019	0.075	60.3
reach average	4.27	3.03	0.0014	0.070	56.9

a)

b)

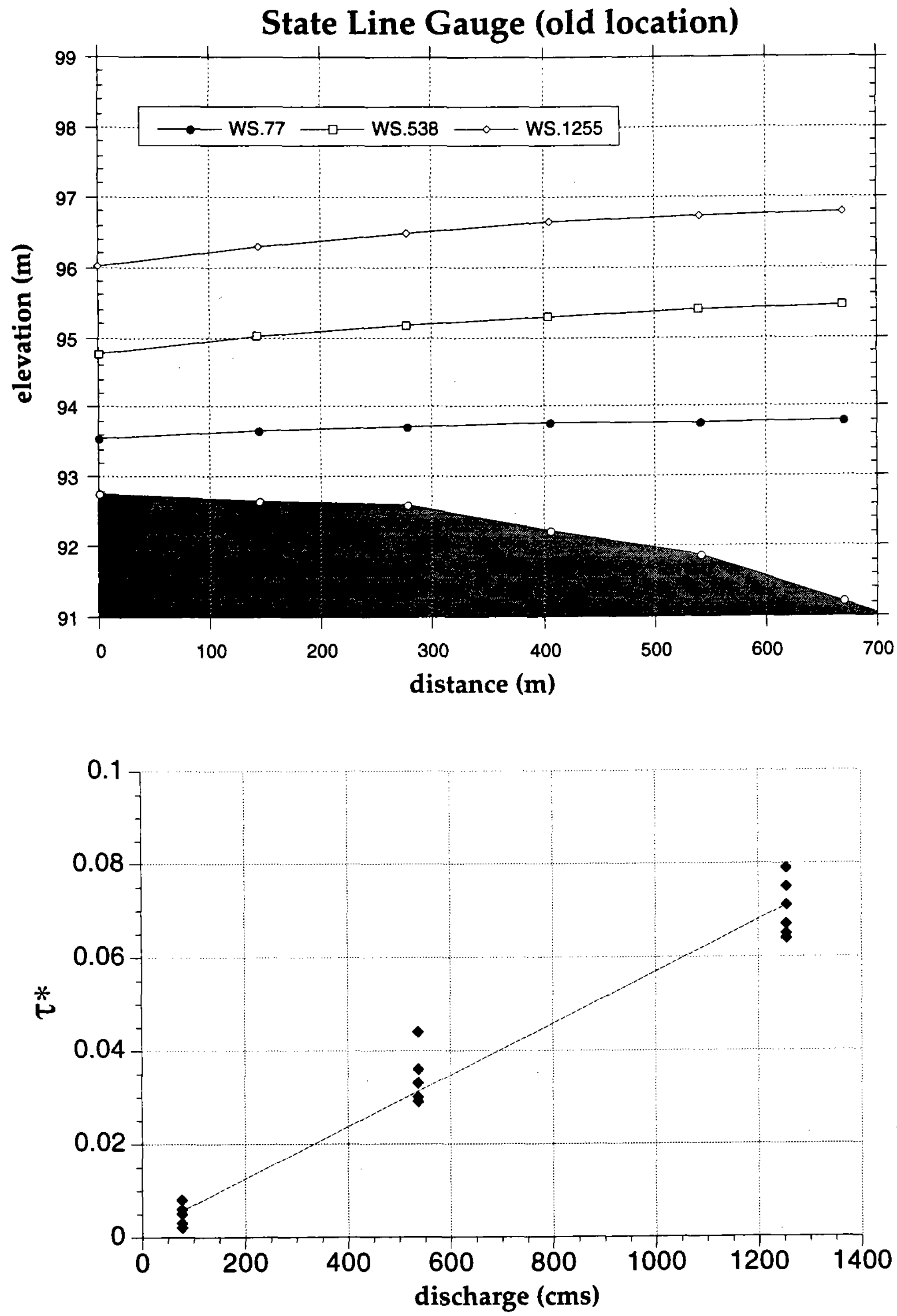


Figure 22. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at the Old Gauge site

Table 10. Summary of Hydraulic Data (USGS Gage, New Site)

discharge = 76 m3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	0.99	0.77	0.0007	0.008	6.7
2	1.07	0.76	0.0006	0.008	6.4
3	0.77	0.83	0.0011	0.010	8.5
4	0.72	0.87	0.0013	0.012	9.5
5	0.54	1.16	0.0035	0.023	18.7
6	0.56	1.72	0.0074	0.051	40.9
reach average	0.78	1.02	0.0025	0.019	15.1

discharge = 387 m3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	2.11	1.71	0.0011	0.028	23.0
2	2.11	1.83	0.0013	0.032	26.2
3	1.77	1.82	0.0016	0.034	27.4
4	1.64	1.93	0.0020	0.039	31.8
5	1.38	2.30	0.0035	0.059	47.5
6	1.75	2.14	0.0022	0.047	38.0
reach average	1.79	1.95	0.0019	0.040	32.3

discharge = 1255 m3/s

xsect	h (m)	u (m/s)	S_f	τ^*	τ (N/m^2)
1	3.79	2.61	0.0011	0.051	41.3
2	3.71	2.94	0.0014	0.065	52.6
3	3.31	3.06	0.0018	0.073	59.0
4	3.11	3.25	0.0022	0.084	68.1
5	2.79	3.63	0.0032	0.109	88.3
6	3.20	3.43	0.0024	0.093	75.4
reach average	3.32	3.15	0.0020	0.079	64.1

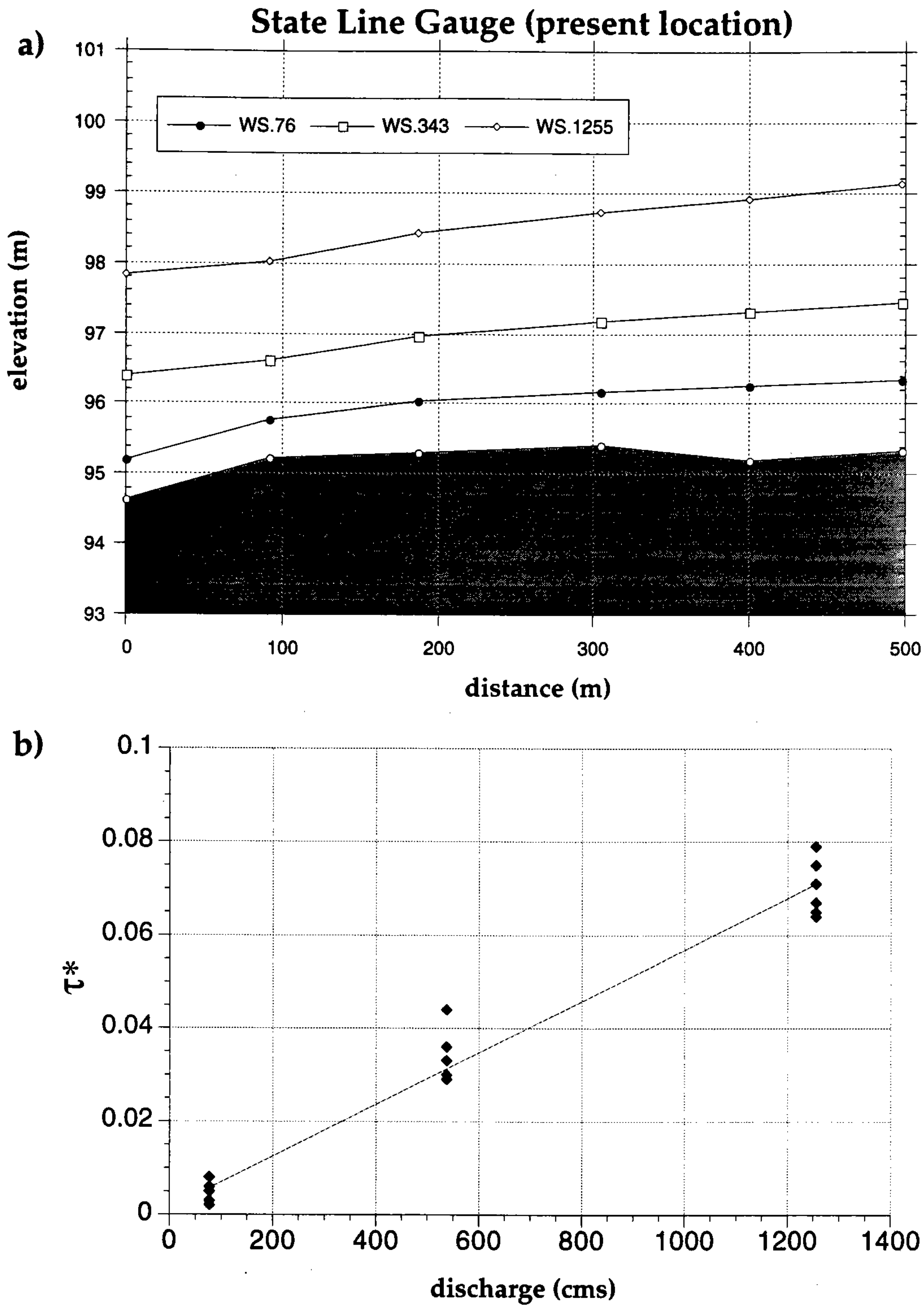


Figure 23. a) Bed and water surface profiles, and b) the relationship between dimensionless shear stress and discharge at the New Gauge site

Conclusion

The results of our calculations indicate that flows similar to the peak of the 1993 runoff produce a shear stress approximately equal to two times the value for initial motion ($\tau^* = 0.06$). The results of Andrews (1984) and Parker (1979) indicate that two times the value for initial motion should be near the threshold for bank erosion, and that this commonly occurs near bankfull flow. Our observations of the effects of the 1993 flows are consistent with this since the peak flows were near bankfull and we noted freshly deposited gravel bars throughout the study reach, but only isolated areas of bank erosion. Our calculations also predict that the flows of 1994 should have caused little or no movement of bed material. Again, our field observations are consistent with this result. We did not observe any large changes in gravel bars, and a study of tagged gravels near the Redlands Parkway showed no movement of particles during the 1994 runoff.

The results of our calculations for above the Gunnison River confluence (the 15 mile reach) indicate that a flow of approximately 300 cms (10,600 cfs) is needed for initial motion of the bed material, and a flow of 625 cms (22,000 cfs) will cause significant motion (Table 11). Results for below the Gunnison River confluence (the 18 mile reach and Ruby-Horsethief Canyon) indicate that a flow of approximately 450 cms (15,900 cfs) will initiate movement of the bed material and a discharge of 1000 cms (35,300 cfs) causes significant movement (Table 11). This flow range is similar to results for a single site in the 18 mile reach reported in our previous study (Van Steeter and Pitlick, 1994).

Table 11. Summary of Flow Modeling Site Characteristics and Conditions for Transport of D_{50}

location (river mile)	D_{50} (mm)	shear stress (N/m^2) initial	signif.	discharge (cms) initial	signif.
Palisade (184.2)*	75	37	73	350	725
Corn (177.3)*	48	24	47	250	525
Redlands (166.0)	57	28	55	420	1100
Site (162.4)	55	27	53	575	1300
Old gauge (139.5)	50	24	49	525	1050
New gauge (134.0)	50	24	49	275	875

* indicates sites above the confluence of the Gunnison River

Flows in the above range are important to fish habitat since they are responsible for both creating new channel forms and "flushing" fine sediments from the gravel bed. Gravel bars and islands increase habitat quality by providing an array of habitats for several life stages, and it is generally believed by biologists that the endangered fish prefer "clean" substrates (Osmundson and Kaeding, 1991; Tyus and Karp, 1989; Hamman, 1981). Flows greater than the threshold for motion should be important for winnowing fines from the bed because fine particles "hide" in the interstices of the framework gravels and are not removed until that framework is disrupted (Stalnaker et al., 1989). It is likely that some winnowing of surface fines occurs at lower flows but the deeper interstices which are important for invertebrate production and egg incubation would not be flushed. The flows which create new channel features are likely to be close to the upper end of the flow range since this is when there is significant transport of bed material.

A final point to consider is vegetation. Vegetation stabilizes bars and banks, and makes them much more resistant to erosion. This study did not directly assess the effects of vegetation on substrate mobility, but it was clear that many bars in the study area have become vegetated by willow and tamarisk. Since it is assumed that maintaining channel complexity is important to endangered fish habitats, attention should be given to suppressing vegetation since it inhibits the movement of the material making up bars and islands. It is likely that consecutive low flow years allow vegetation to become firmly established on channel bars, and thus make the gravels more difficult to entrain than our predictions show. Observations of the 1993 flow showed that many small plants survived this relatively large flow event, so either larger flows or consecutive years of high flow should be needed to remove vegetation from bars and islands in the reach.

DOWNSTREAM HYDRAULIC GEOMETRY

If flows are prescribed for maintenance and creation of fish habitats in the Grand Valley and Ruby-Horsethief Canyon, it is important to understand how these flows affect sediment transport for the entire reach. In order to do this, we measured main channel cross-sections to examine longitudinal trends in bankfull width, depth and shear stress.

These measurements are essential for putting our flow modeling sites in a larger context, and for understanding the general character of the river. The information on the occurrence of wide and relatively shallow areas, which represent areas of complex channel, indicate the general frequency of this habitat type. Also, the calculation of bankfull dimensionless shear stress provides a measure of where bank erosion, and an increase in channel complexity, might occur. This can be estimated since bank erosion generally begins when the material at the base of the bank starts to move, and this occurs at a dimensionless shear stress of 0.06 (Parker, 1979).

The method used for this analysis is similar to that described previously for the evaluation of coarse sediment transport, but the water surface slope was used instead of the friction slope. The assumption that the water surface slope is a reasonable estimate of the friction slope was tested at the flow modeling sites, and results showed that they were similar.

Results

Cross-sections in the Grand Valley are generally wider and shallower than in Ruby-Horsethief Canyon (Figs. 24 and 25, Tables 12 and 13). This is reasonable since the Canyon reach is confined by bedrock walls in most areas which results in a narrower and deeper channel. The bankfull dimensionless shear stress ranges between 0.039 and 0.106 for the Grand Valley and between 0.0370 and 0.094 for Ruby-Horsethief Canyon. This range shows that there are areas of relatively high and low shear stress at bankfull discharge which would cause local scour and fill. This is expected since at high flows pools are generally scoured and riffles accumulate coarse particles (Leopold et al., 1964). The mean value for both reaches is near 0.06 which indicates that bankfull flow causes significant transport of bed material, and that it produces a shear stress near the threshold for bank erosion. More importantly, these values are similar to bankfull results at the flow modeling sites where the dimensionless shear stress is also near 0.06. This indicates that prescribed flows based upon the flow modeling sites will yield similar results throughout the entire reach.

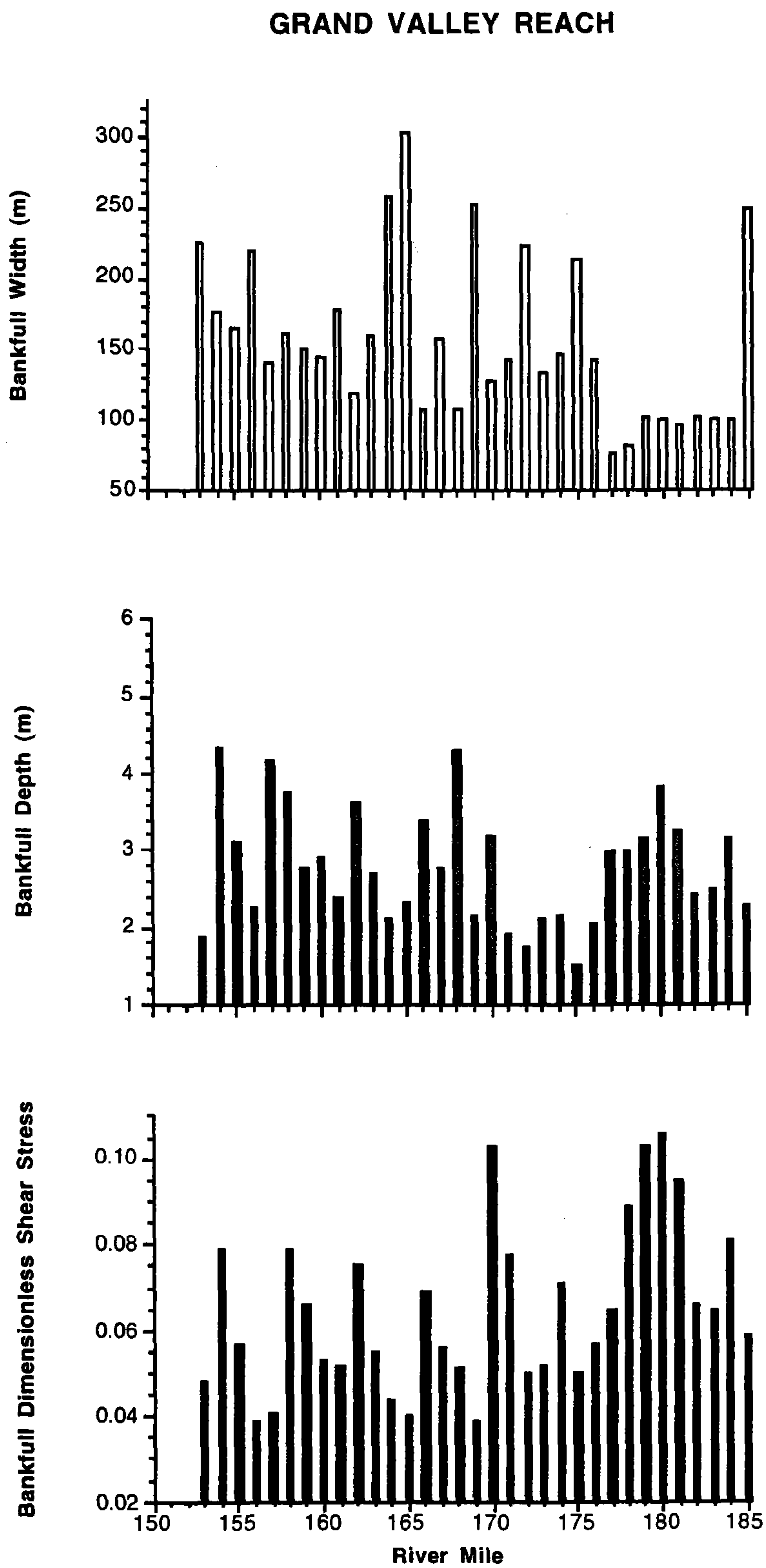


Figure 24. Bankfull width, depth, and dimensionless shear stress by river mile for the Grand Valley

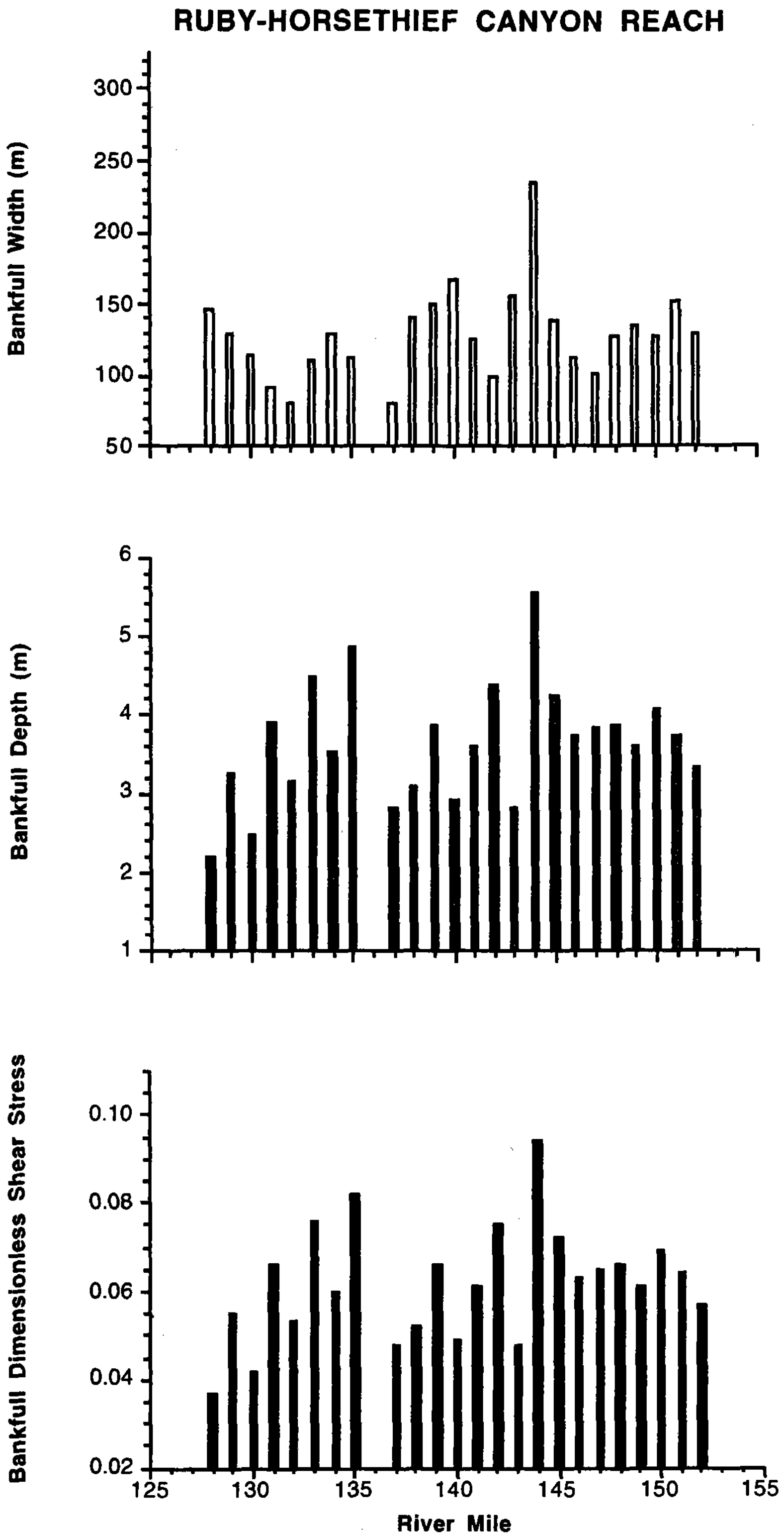


Figure 25. Bankfull width, depth, and dimensionless shear stress by river mile for Ruby-Horsethief Canyon

Table 12. Bankfull Hydraulic Geometry for the Grand Valley Reach

River Mile	A (m^2)	w (m)	h (m)	$\tau^{(1)}$	$\tau^{*\,(2)}$
185	571	249	2.29	56.4	0.059
184	318	101	3.15	77.4	0.081
183	253	101	2.51	62.5	0.065
182	249	102	2.43	63.7	0.066
181	318	97	3.27	90.4	0.095
180	383	99	3.85	101.0	0.106
179	321	102	3.14	98.0	0.103
178	246	82	2.99	85.3	0.089
177	226	76	2.97	61.7	0.065
176	296	143	2.07	54.0	0.057
175	317	213	1.50	47.4	0.050
174	317	147	2.16	68.1	0.071
173	284	133	2.13	49.2	0.052
172	391	223	1.75	47.6	0.050
171	274	142	1.93	74.8	0.078
170	409	128	3.19	98.0	0.103
169	547	254	2.15	36.9	0.039
168	464	108	4.31	48.8	0.051
167	438	158	2.77	53.4	0.056
166	364	107	3.40	65.5	0.069
165	713	303	2.34	37.8	0.040
164	549	259	2.12	41.6	0.044
163	430	159	2.70	52.7	0.055
162	430	118	3.64	71.3	0.075
161	427	179	2.39	49.6	0.052
160	421	145	2.90	50.1	0.053
159	418	150	2.78	62.6	0.066
158	609	162	3.76	75.3	0.079
157	591	141	4.18	39.0	0.041
156	494	219	2.26	37.2	0.039
155	518	166	3.12	54.0	0.057
154	762	176	4.33	74.9	0.079
153	425	226	1.89	45.5	0.048

(1) τ computed using mean slope for one mile above and below site

(2) τ^* computed assuming D_{50} = 59 mm

Table 13. Bankfull Hydraulic Geometry for Ruby-Horsethief Canyon Reach

River Mile	A (m^2)	w (m)	h (m)	τ (1)	τ^* (2)
152	434	130	3.34	45.9	0.057
151	569	152	3.75	51.5	0.064
150	516	127	4.07	55.9	0.069
149	484	135	3.60	49.4	0.061
148	497	128	3.88	53.3	0.066
147	391	102	3.83	52.7	0.065
146	418	112	3.74	51.4	0.063
145	585	138	4.25	58.4	0.072
144	1306	235	5.55	76.3	0.094
143	440	156	2.81	38.6	0.048
142	434	99	4.40	60.4	0.075
141	455	126	3.60	49.5	0.061
140	486	167	2.91	39.9	0.049
139	586	151	3.88	53.4	0.066
138	432	141	3.07	42.2	0.052
137	225	80	2.83	38.9	0.048
136	"Black Rocks"	--	--	--	--
135	547	113	4.85	66.6	0.082
134	457	129	3.53	48.5	0.060
133	495	110	4.50	61.8	0.076
132 RC(3)	252	80	3.14	43.2	0.053
131 RC(3)	361	92	3.91	53.7	0.066
130	281	114	2.47	34.0	0.042
129	423	130	3.26	44.7	0.055
128	324	147	2.20	30.2	0.037

(1) τ computed assuming an average slope of 0.0014

(2) τ^* computed assuming D_{50} = 50 mm

(3) values computed for main (right) channel only

SUMMARY

Changes in the physical habitats of the Colorado squawfish and razorback sucker may affect both the adults' ability to reproduce, and the survival of larval fish (Osmundson and Kaeding, 1991). In this study we have documented historic changes in channel morphology, recent effects of discharge on backwater habitats, and we have determined the range of flows which are needed to maintain and create channel complexity.

Aerial Photograph/GIS Analysis

Our GIS analysis shows that there has been a general decrease in the area of most channel features throughout the Grand Valley and Ruby-Horsethief Canyon (Figures 3,6,7). Changes are consistent for both comparisons of 1954-1968 and 1937-1993. The 1954-1968 analysis documents channel change during a period of below average peak flows, and the 1937-1993 analysis shows channel change over a longer period which includes the extremely high flows of 1983 and 1984. In either case, there was a decrease in water, island, and side channel/backwater area in the Grand Valley, and a decrease in water and side channel/backwater area in Ruby-Horsethief Canyon. The analysis of Ruby-Horsethief Canyon showed an increase in island area through time which could be due to the accretion of sediment to islands, but these islands have not become part of the floodplain as in the Grand Valley reach. In summary, there has been a general decrease in channel complexity through time, which indicates a decrease in available low velocity habitats.

Field Studies

Studies of side channel/backwater sites showed some changes in channel morphology from the relatively high flows of 1993, but very little change in 1994. These effects are consistent with our flow modeling results which show that there was significant transport of bed material in 1993, but very little in 1994.

The upstream entrance of flow to the three side channel field sites are composed primarily of gravel, and showed very little change throughout both years. Fine sediment was deposited near the banks in 1993, but overall changes to the main entrance of flow were small.

Mid-sections of the side channel sites generally showed some scouring of fine sediment from the thalweg, and the deposition of fine sediment on the banks in 1993, but there were not substantial changes during the 1994 season. The net result was generally a deeper and narrower channel from 1993 runoff and some filling with sediments during 1994.

The downstream end of these sites control fish access into the backwater at moderate or low flows. These areas showed scouring with the entrance to the backwater becoming deeper in 1993, unless vegetation stabilized the substrate. In 1994 this area showed a small amount of re-filling with sediment at site 2, and significant filling at site 3. Site 1 showed very little change throughout both seasons due to lower water velocities and vegetation.

In general, the flows of 1993 caused channel change at our sites where there was predominantly silt and sand, but the morphology of gravel areas did not change significantly. Vegetation clearly stabilized sediments, and was abraded but not uprooted in 1993. The 1994 flows were relatively small which resulted in deposition of fine sediment in some areas.

Evaluation of Coarse-Sediment Transport

Habitats for endangered fish in the upper Colorado River are formed by coarse sediment that moves only at discharges well in excess of the mean annual flow. An analysis of the relation between shear stress and discharge at four sites in the Grand Valley indicate that the bed material is at the threshold for motion at a discharge of 300 cms (10,600 cfs) above the confluence of the

Gunnison River, and 450 cms (15,900 cfs) below the confluence. This flow is ~3.0 times the mean annual flow. Significant movement of the bed material occurs at a discharge of 625 cms (22,000 cfs) above the Gunnison, and 1,000 cms (35,300 cfs) below its confluence. A flow of this magnitude is at least a 5-year flood. Peak flows in 1993 exceeded 1200 cms (44,000 cfs) and it was evident that gravel movement was wide spread and that fine sediment was winnowed from the bed. Our analysis of the downstream hydraulic geometry of the 57 mile reach indicates that the flow modeling sites are generally representative of the entire reach.

Acknowledgments

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References

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted riverbed material, *Bull. Geol. Soc. Amer.*, v. 94, p. 1225-1231.

Andrews, E.D., 1984. Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado, *Bull. Geol. Soc. Am.*, v. 95, p. 371-378.

Andrews, E.D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *Bull. Geol. Soc. America* . v. 97, p. 1012-1023.

Dingman, S. W., 1984. *Fluvial Hydrology.* , W.H. Freeman and Company, New York, 383 pp.

Graf, W.L., 1978. Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. *Geol. Soc. America Bulletin.* v. 89, p. 1491-1501.

Hamman, R. L., 1981. Spawning and culture of Colorado squawfish in raceways. *Prog. Fish-Cult* , v. 43, p. 173-177.

Henderson, F.M., 1966. *Open Channel Flow,* MacMillan, New York, 522 pp.

Komar, P. D., 1987. Selective gravel entrainment and the empirical evaluation of flow competence. *Sedimentology* , v. 34, v. 1165-1176.

Leopold, L. B., M. G. Wolman and J.P. Miller, 1964. *Fluvial processes in geomorphology.* San Francisco, W.H. Freeman, 522 pp.

Osmundson, D.B. and L.R. Kaeding, 1991. Recommendations for flows in the 15-mile reach during October-June for maintenance and enhancement of endangered fish populations in the upper Colorado River. *U.S. Fish and Wildlife Service, Colorado River Fishery Project.* Grand Junction, Colorado. 82 pp.

Parker, G., 1979. Hydraulic geometry of active gravel rivers, *J. Hydraul. Engr. ASCE,* v. 105 (HY 9), p. 1185-1201.

Parker, G., P. C. Klingeman and D.G. McLean., 1982. Bedload and size distribution in paved gravel-bed streams. *Journal of Hydraulics Div. ASCE,* v. 108 (HY4), p. 544-571.

Pitlick, J. and M. M. Van Steeter, 1994. Changes in morphology and endangered fish habitat of the Colorado River. Colorado Water Resources Research Institute. Fort Collins, Colorado. 24 pp.

Stalnaker, C. B., R. L. Milhous, K.D. Bovee, 1989. Hydrology and hydraulics applied to fishery management in large rivers, p. 13-30. *In* D.P. Dodge (ed.) Proceedings of the International Large Rivers Symposium (LARS), Can. Spec. Publ. Fish. Aquat. Sci. 106.

Stanford, J. A., 1994. Instream flows to assist the recovery of endangered fishes of the Upper Colorado River Basin. National Biological Survey, Biological Report no. 24. 47 pp.

Tyus, H. M., 1992. An instream flow philosophy for recovering endangered Colorado River fishes. *Rivers* , v. 3, p. 27-36.x

Tyus, H.M. and C.A. Karp, 1989. Habitat and streamflow needs of rare and endangered fishes, Yampa River, Colorado. *U.S. Fish and Wildlife Service, Biological Report 89(14).* 27 pp.

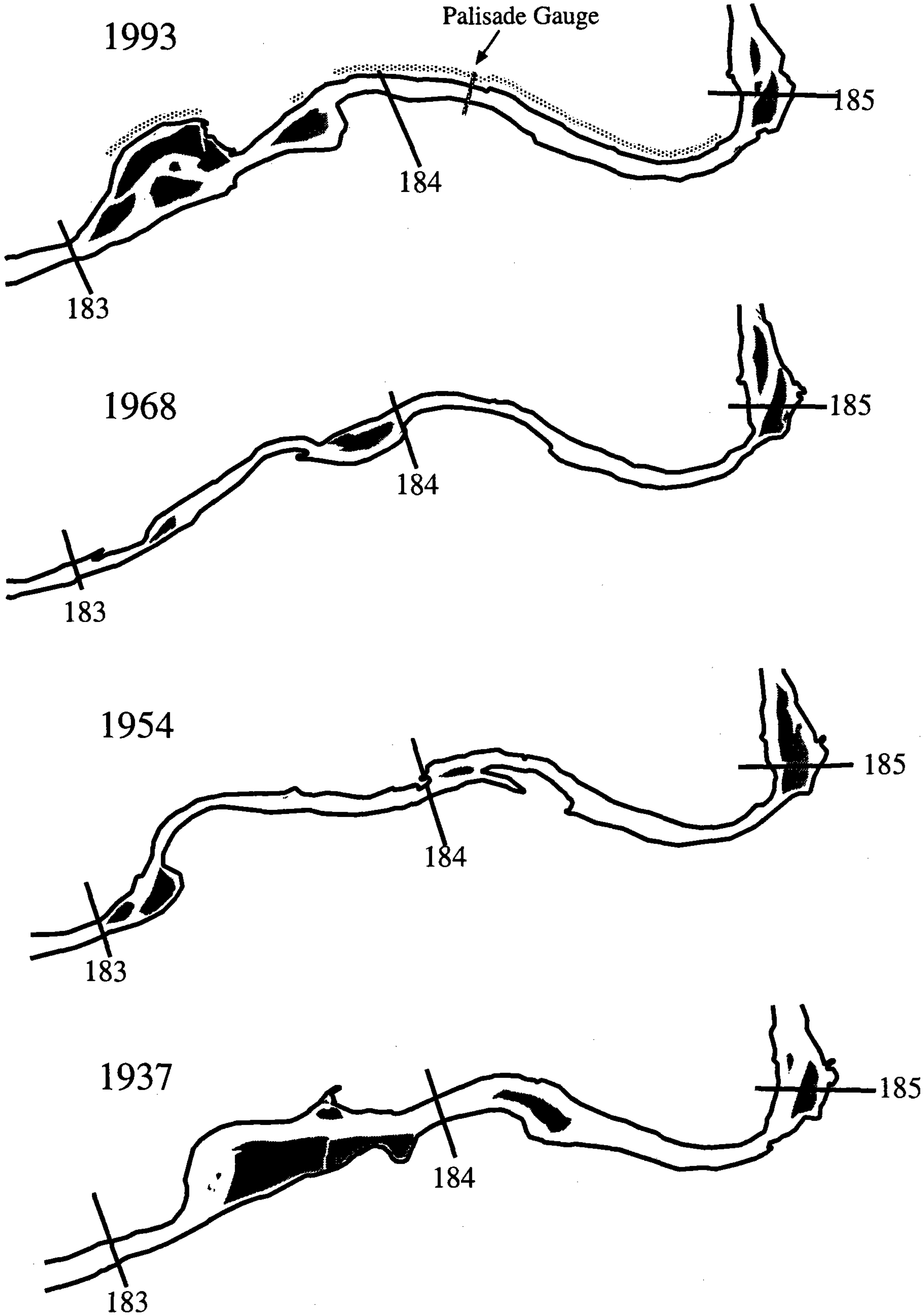
U.S. Fish and Wildlife Service, 1987. Recovery implementation program for endangered fish species of the upper Colorado River Basin, *U.S. Department of the Interior, Fish and Wildlife Service*, Denver, Colorado.

Van Steeter, M. M. and J. Pitlick, 1994. Aerial photograph/GIS analysis and field studies of the 15 and 18 mile reach of the Colorado River. University of Colorado, Boulder. 46 pp.

Wilcock, P. R., 1988. Methods for estimating the critical shear stress of individual fractions in mixed-size sediment. *Water Resources Research* , v. 24, p. 1127-1135.

Williams, G. P. and M. G. Wolman, 1984. Downstream effects of dams on alluvial rivers. *U.S. Geological Survey Professional Paper 1286*, 83 pp.

Appendix I. Maps of the Grand Valley reach for 1937, 1954, 1968, and 1993. (shaded area along bank in 1993 plot indicates bank stabilization)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Palisade Gauge
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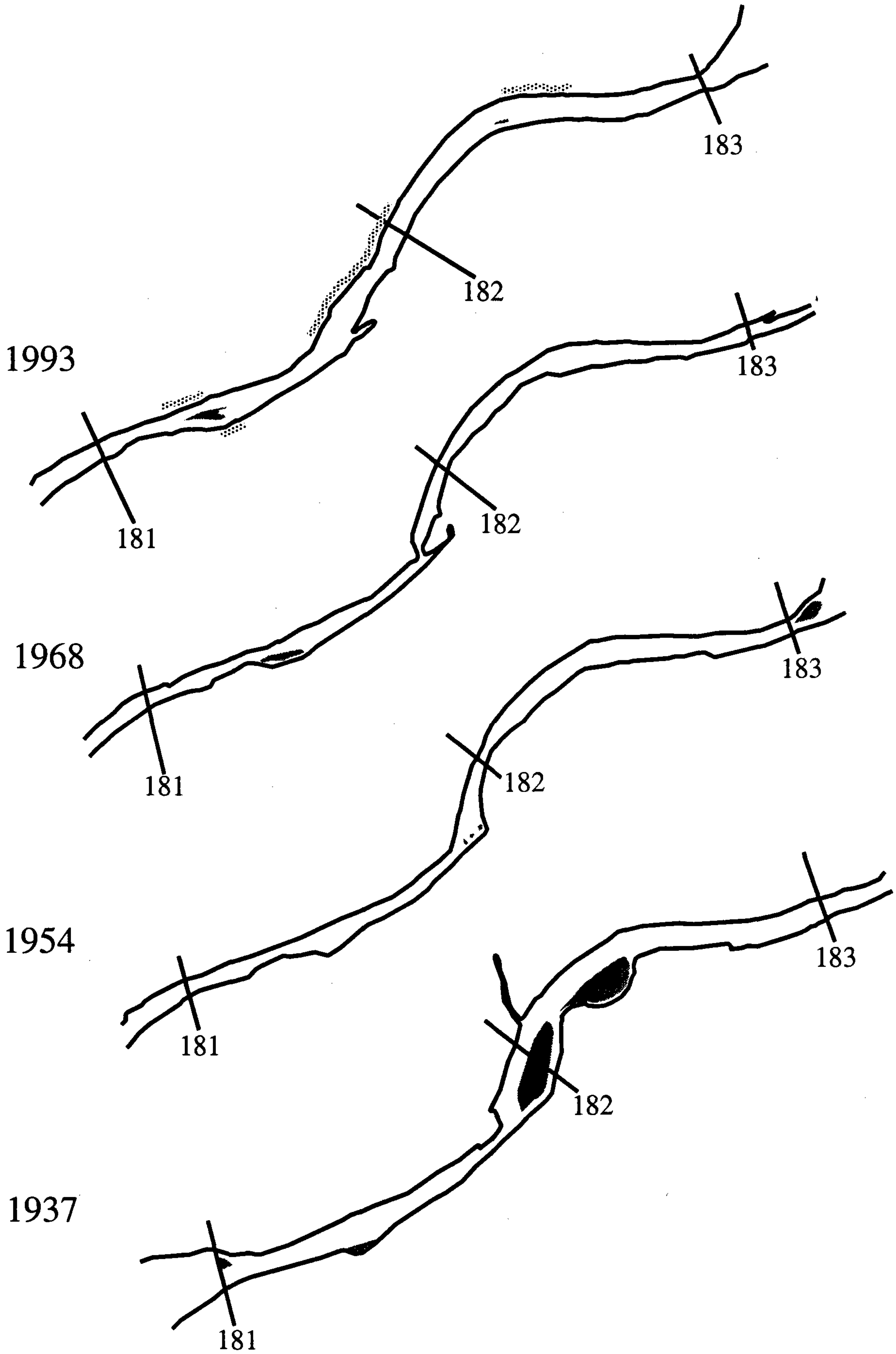
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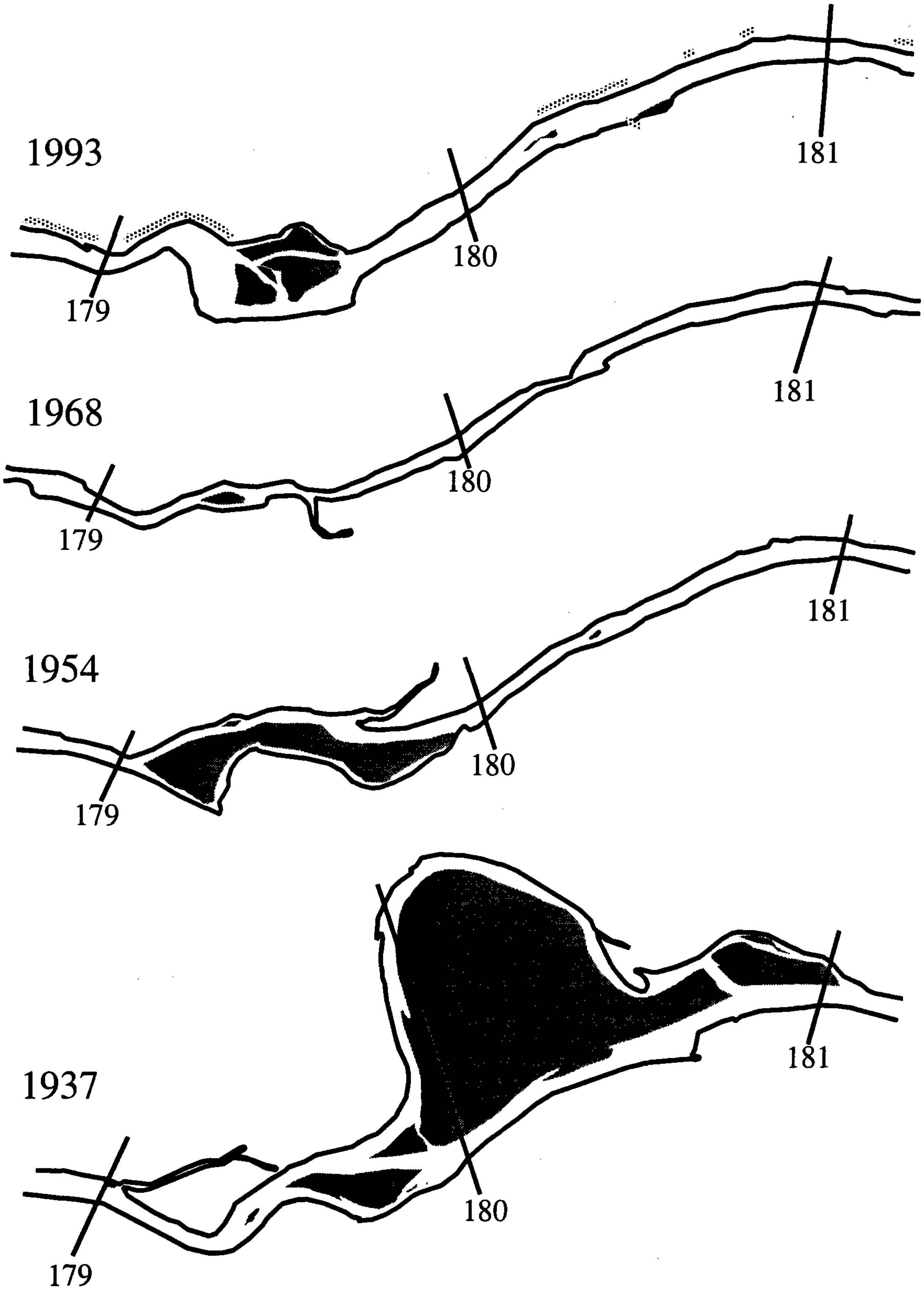
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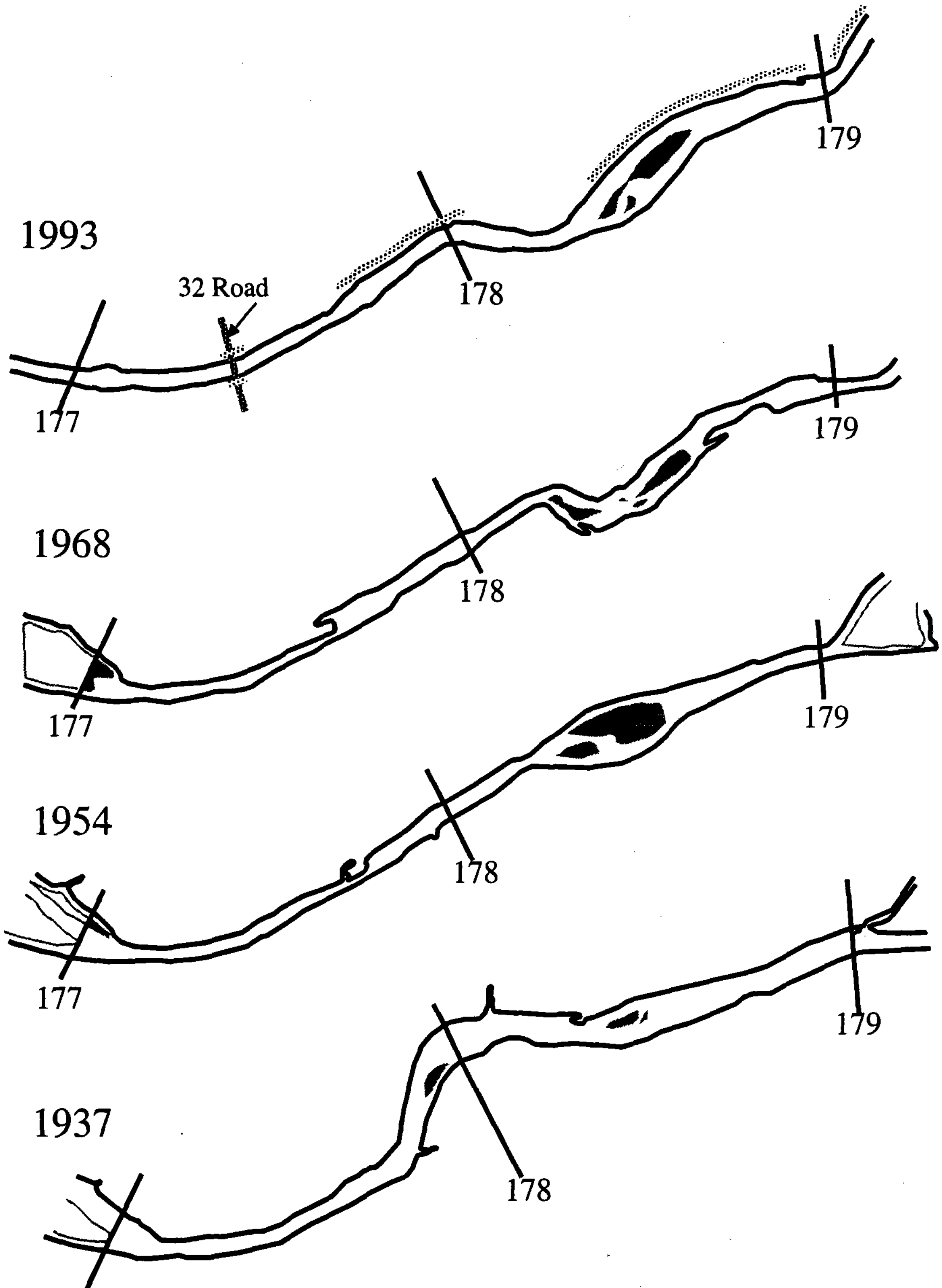
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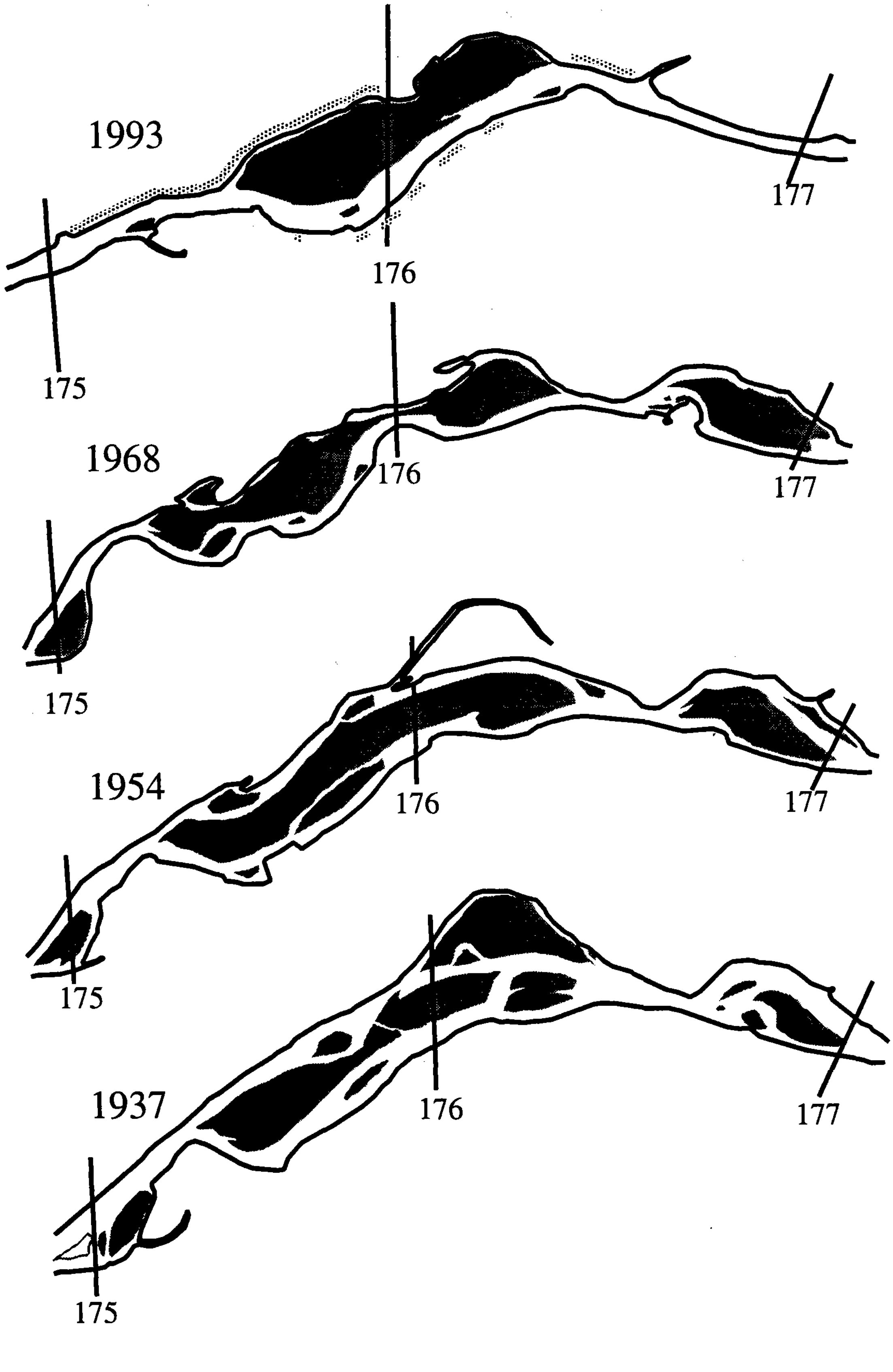
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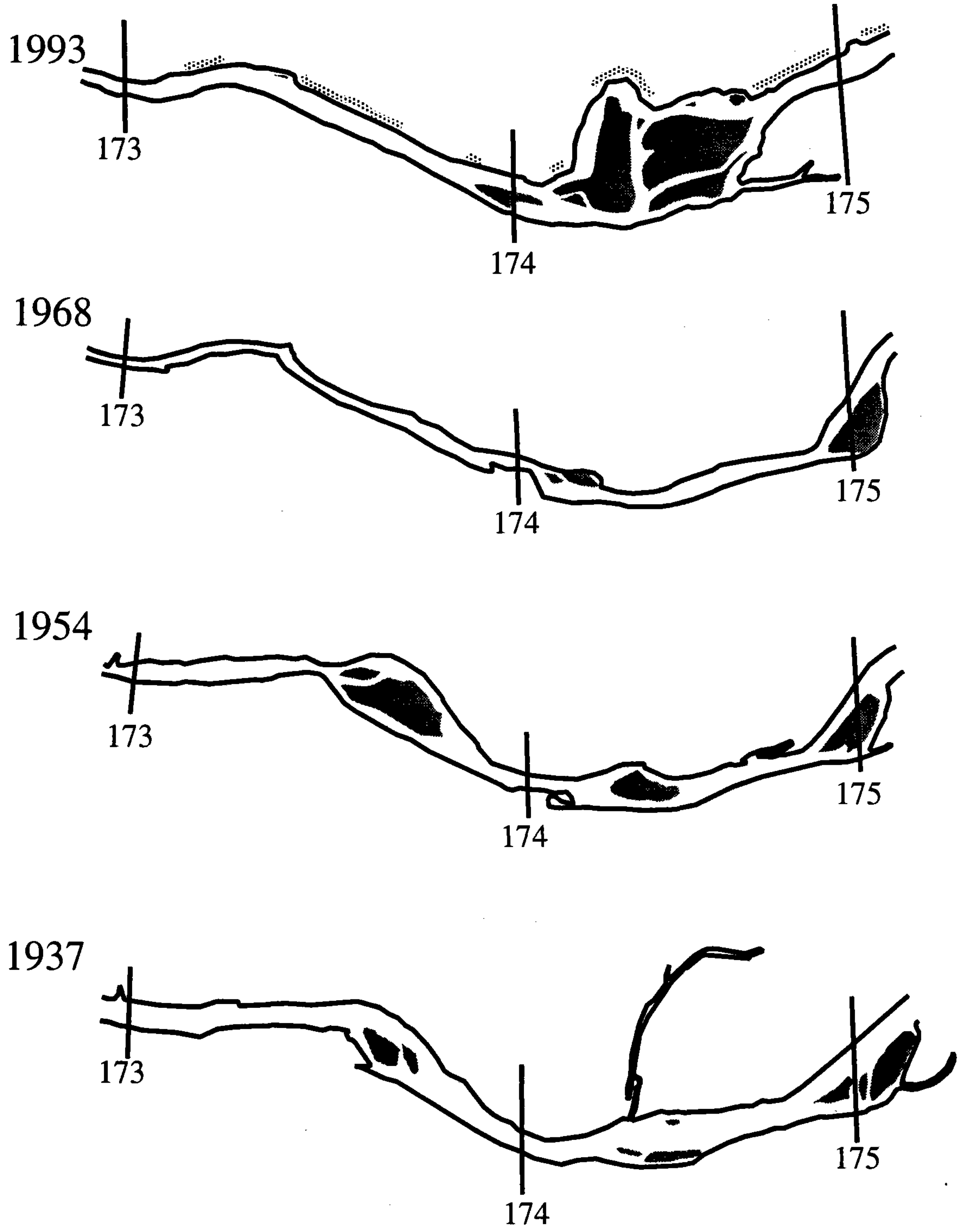
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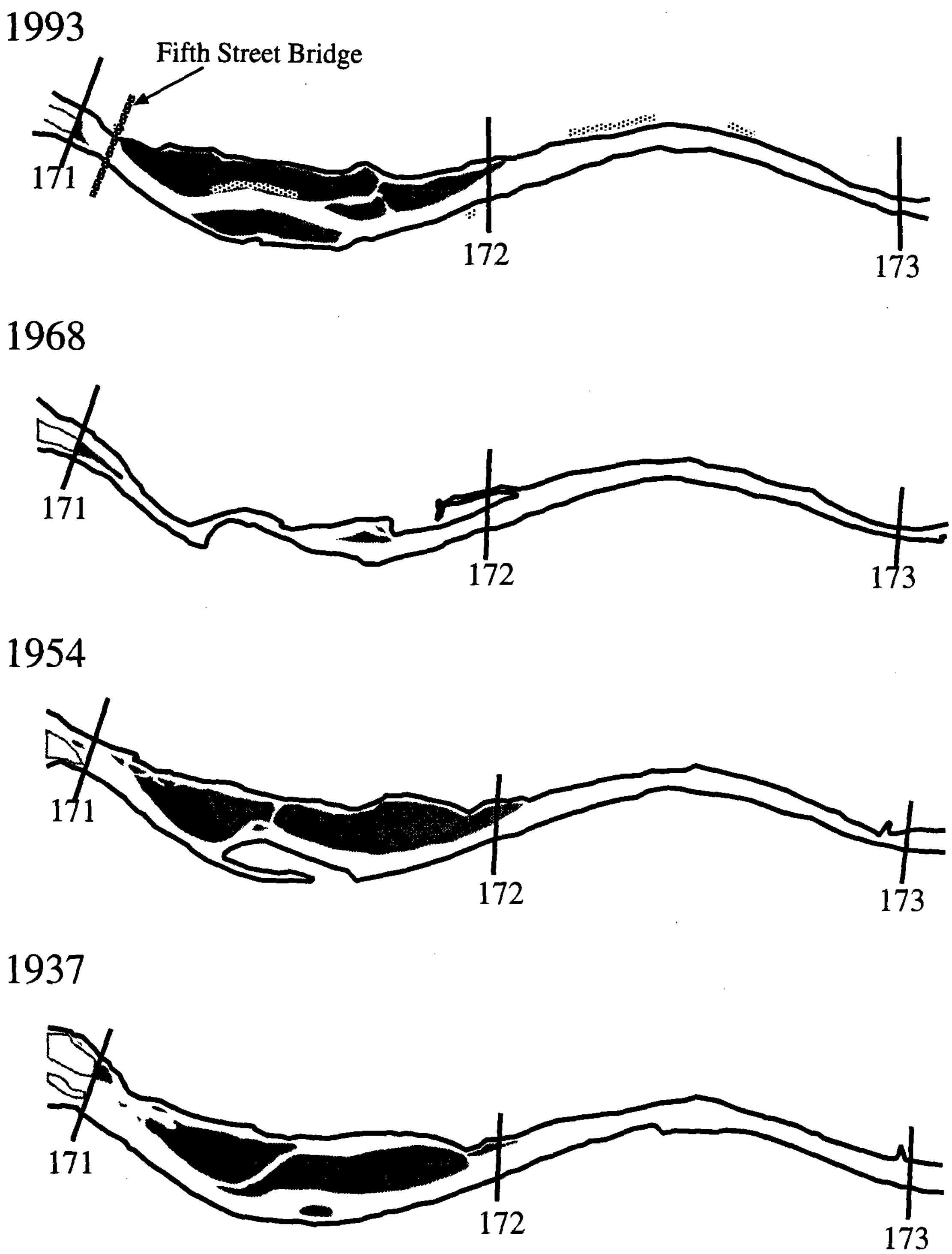
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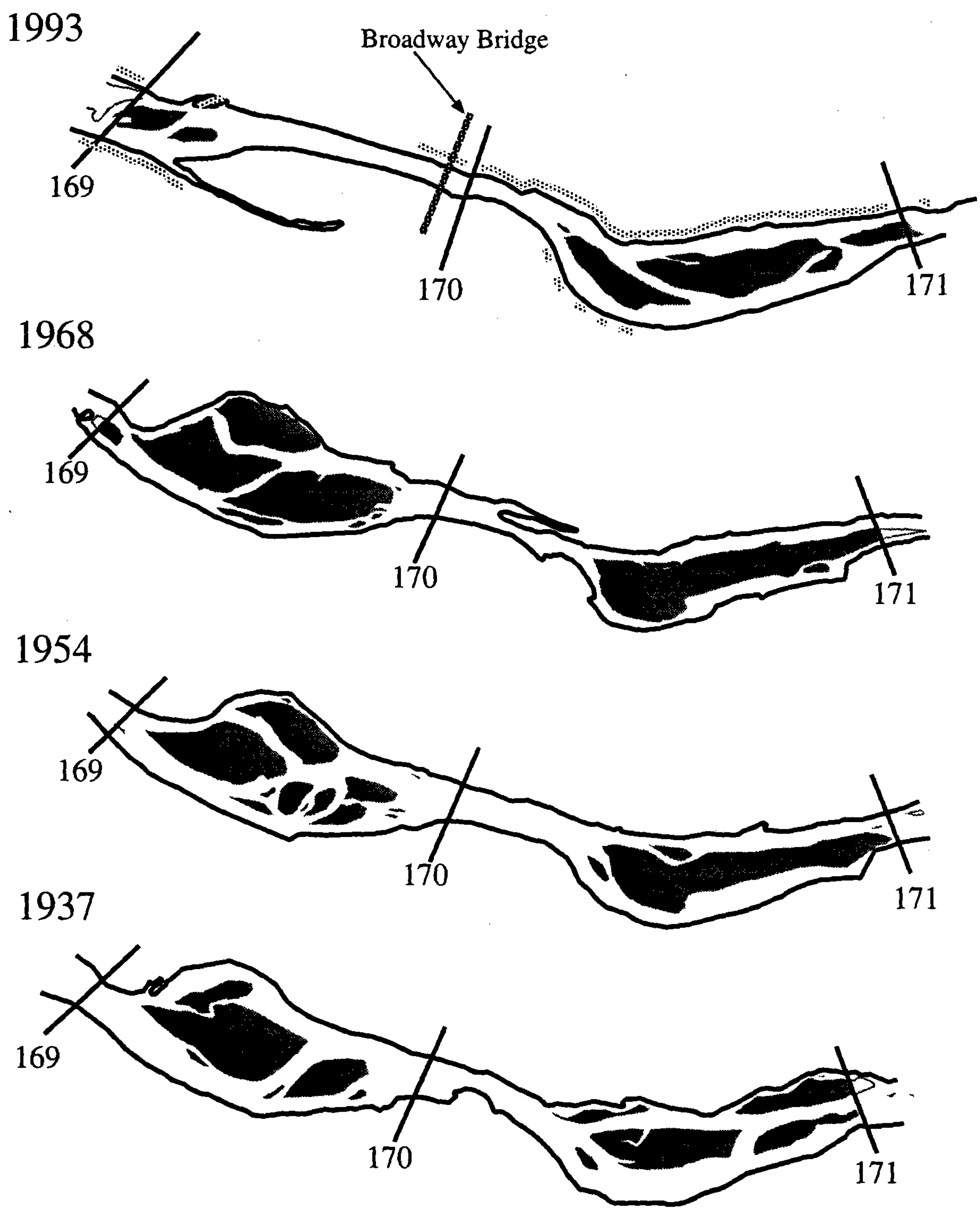
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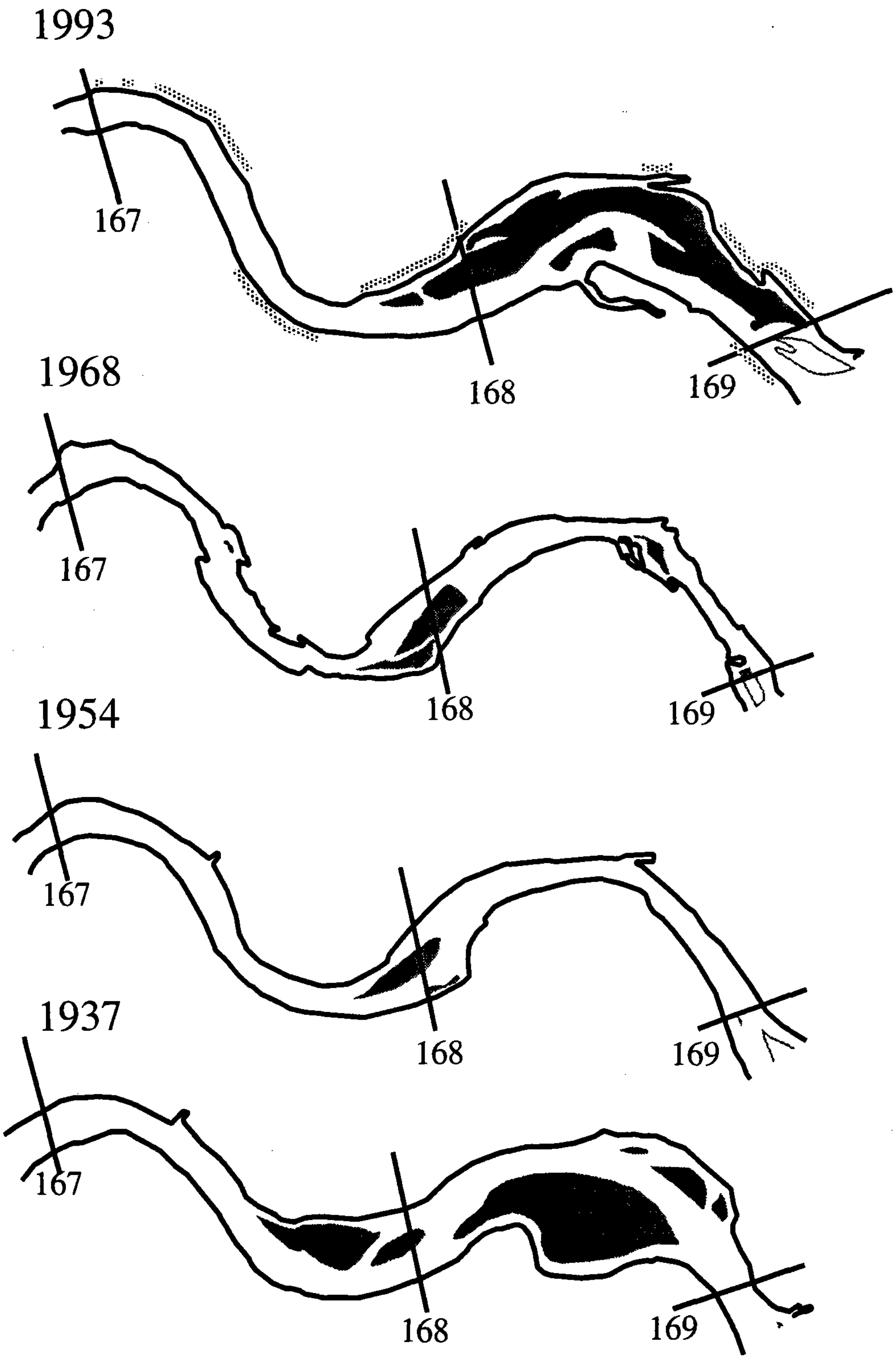
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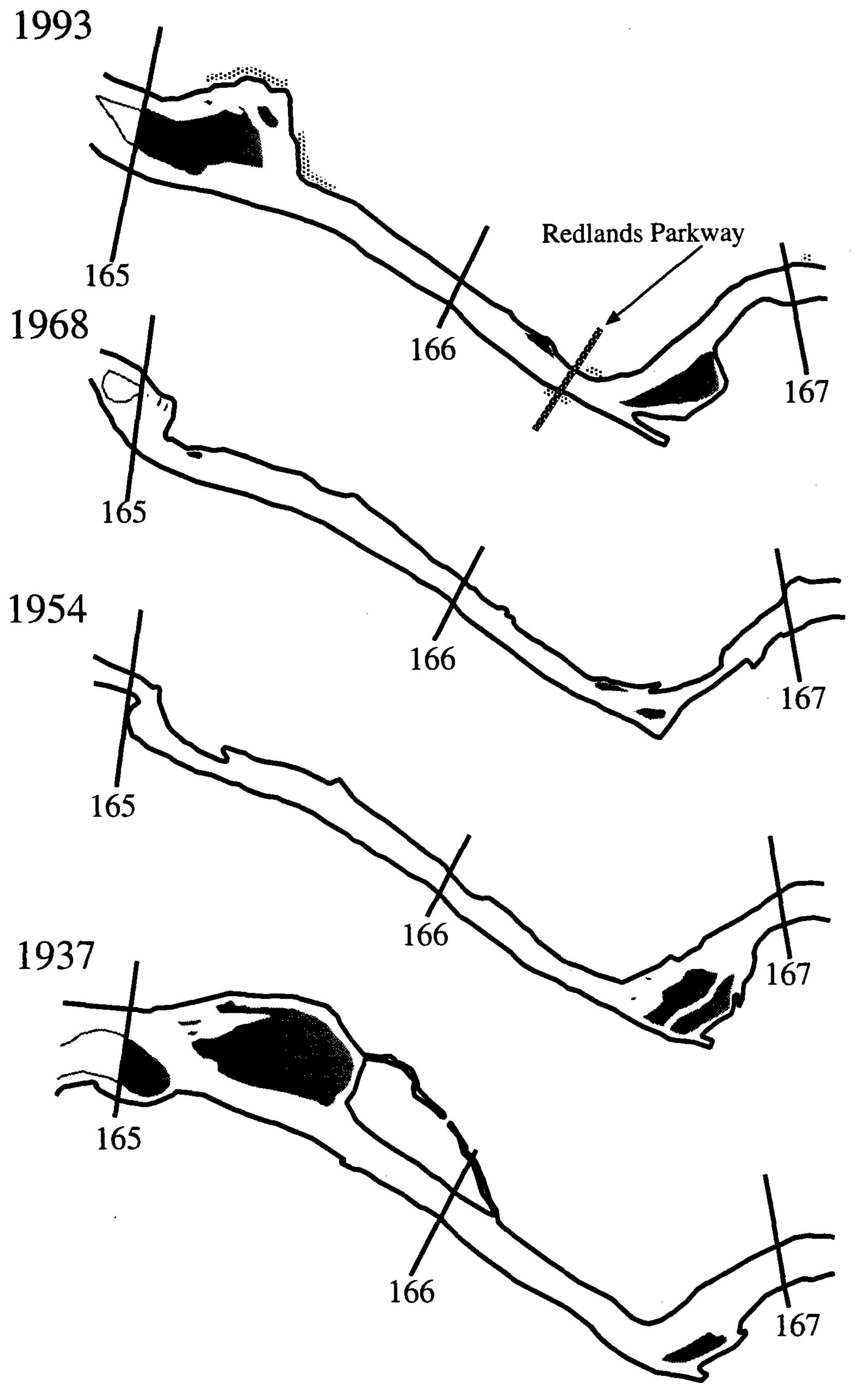
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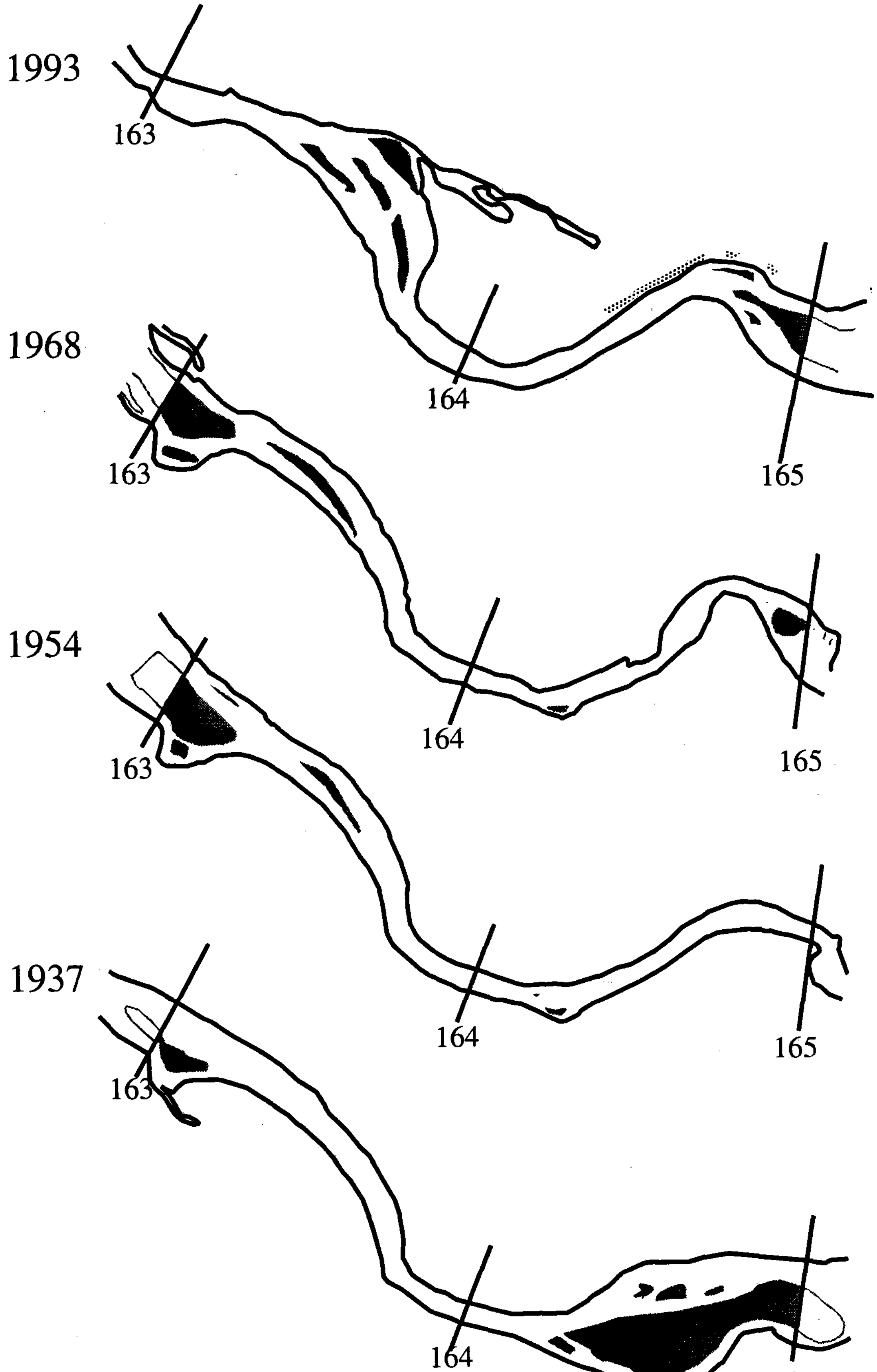

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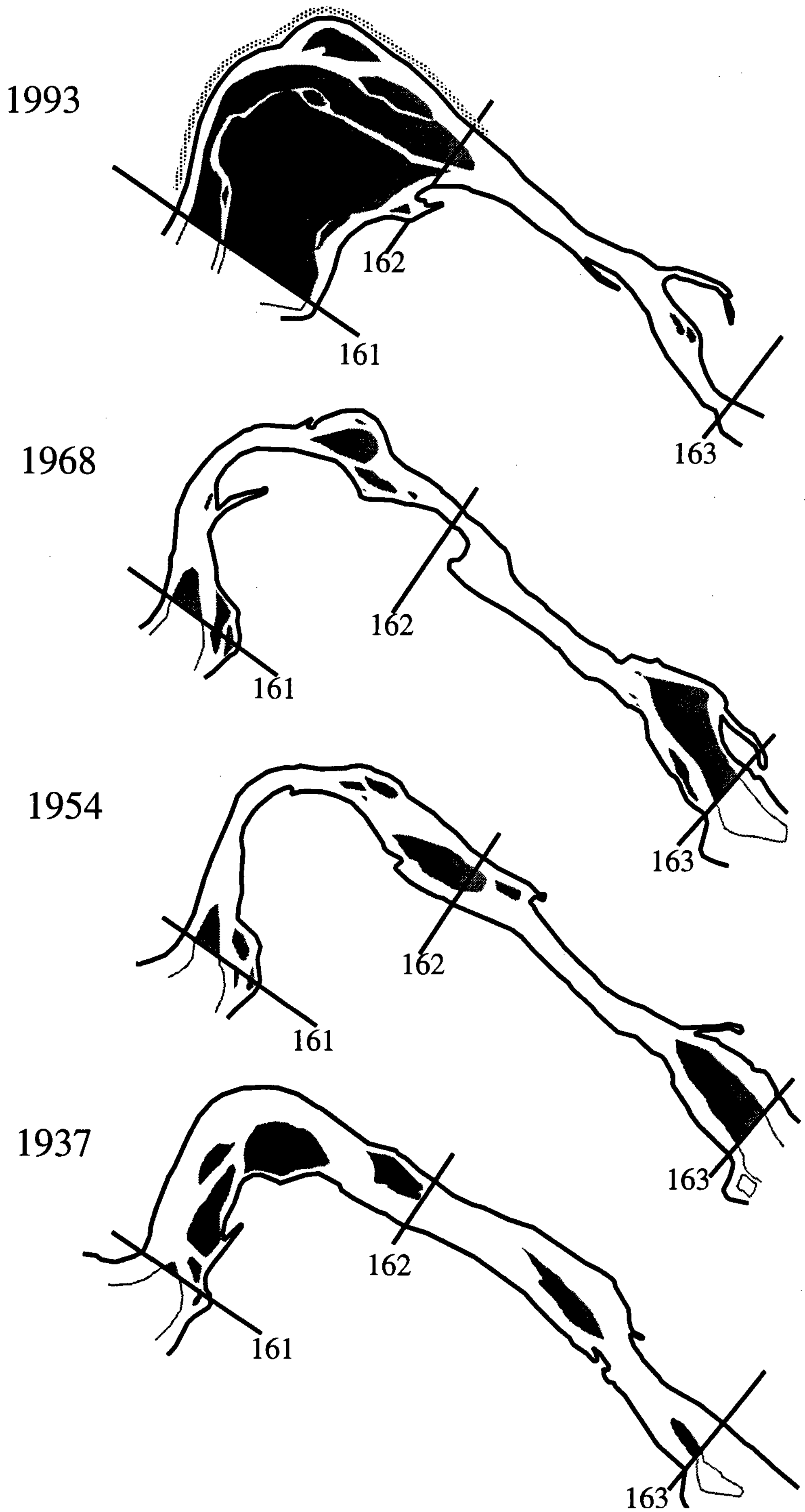
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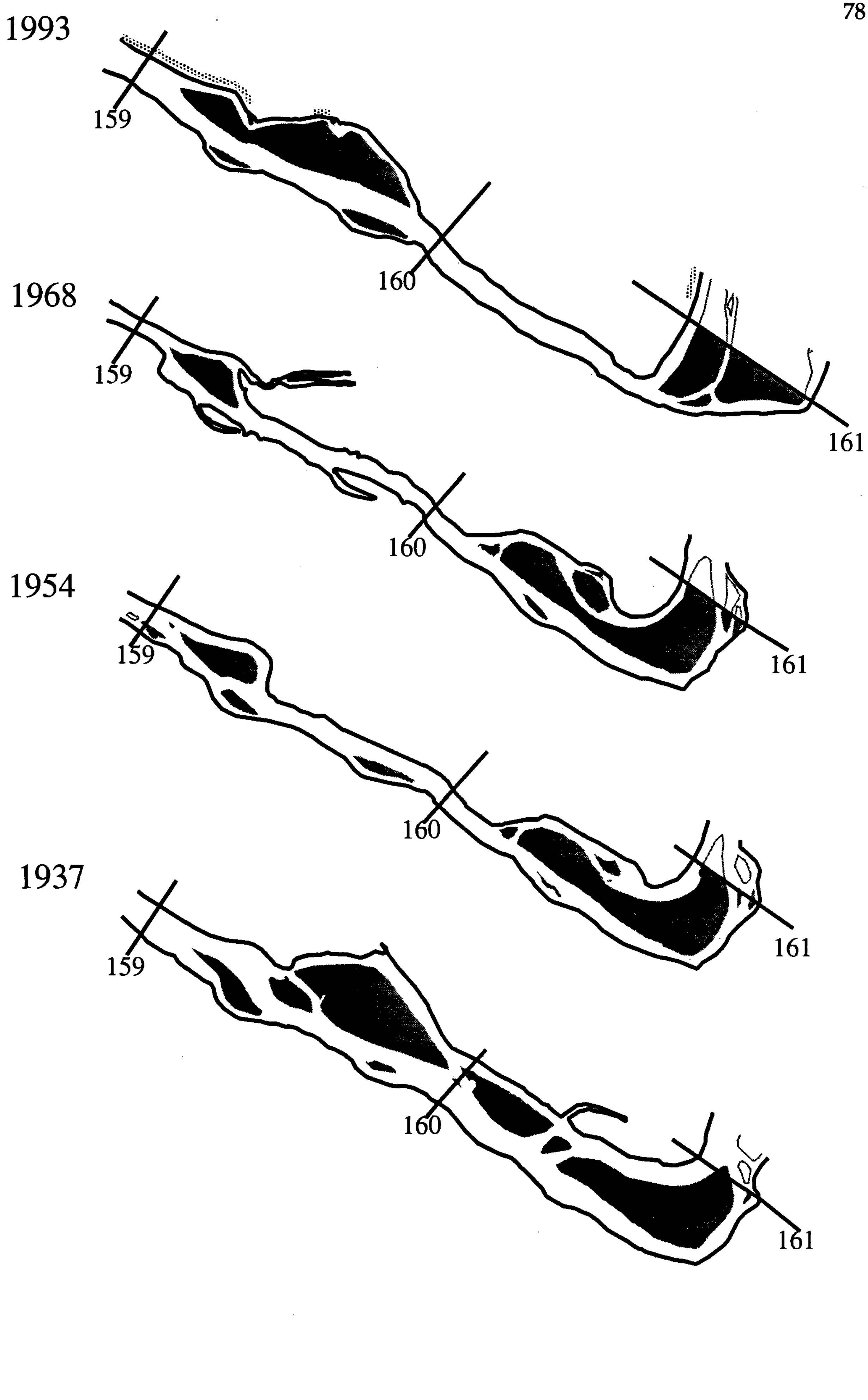
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160
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1968
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1954
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1937
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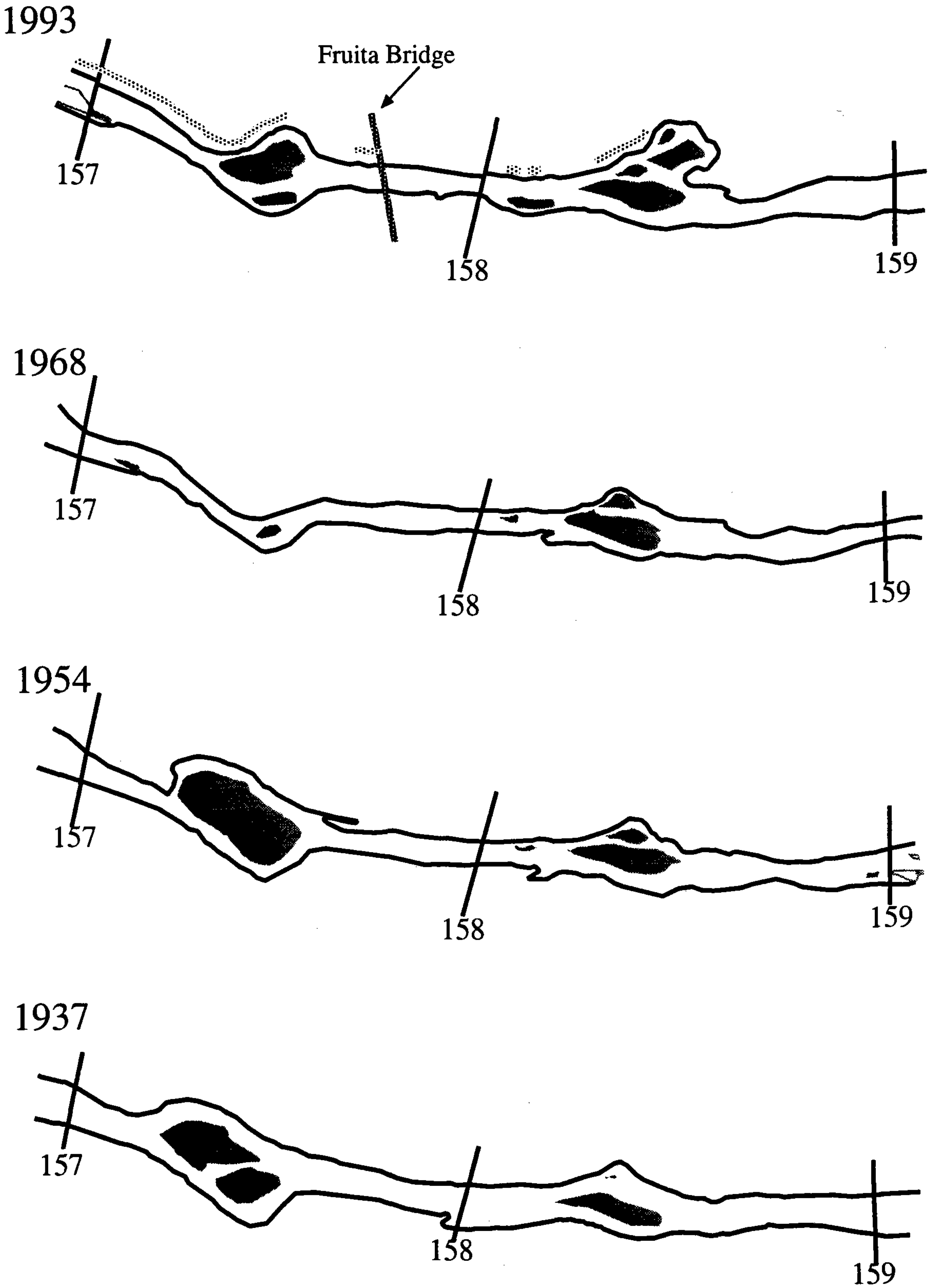
161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Fruita Bridge
157
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1954
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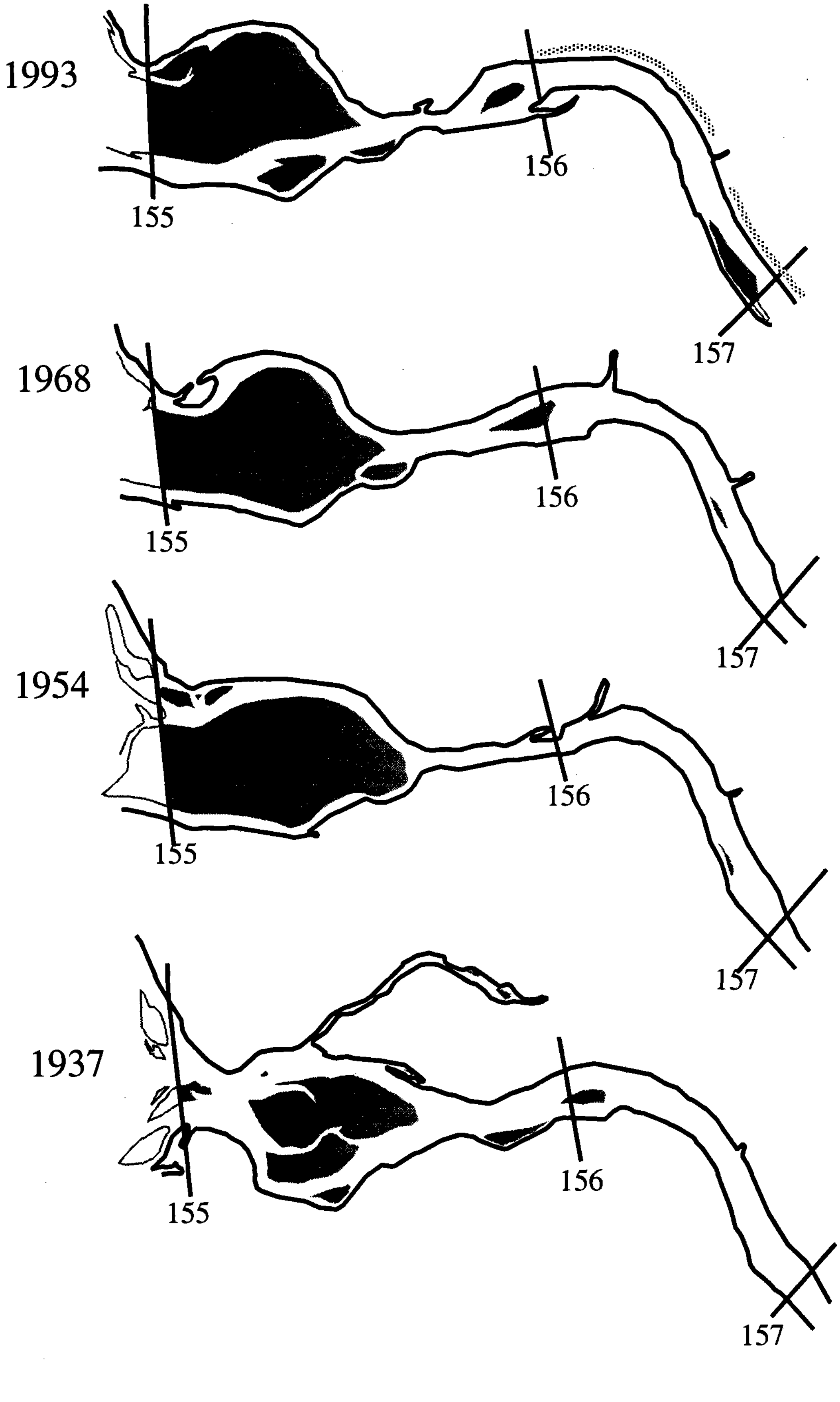
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1954
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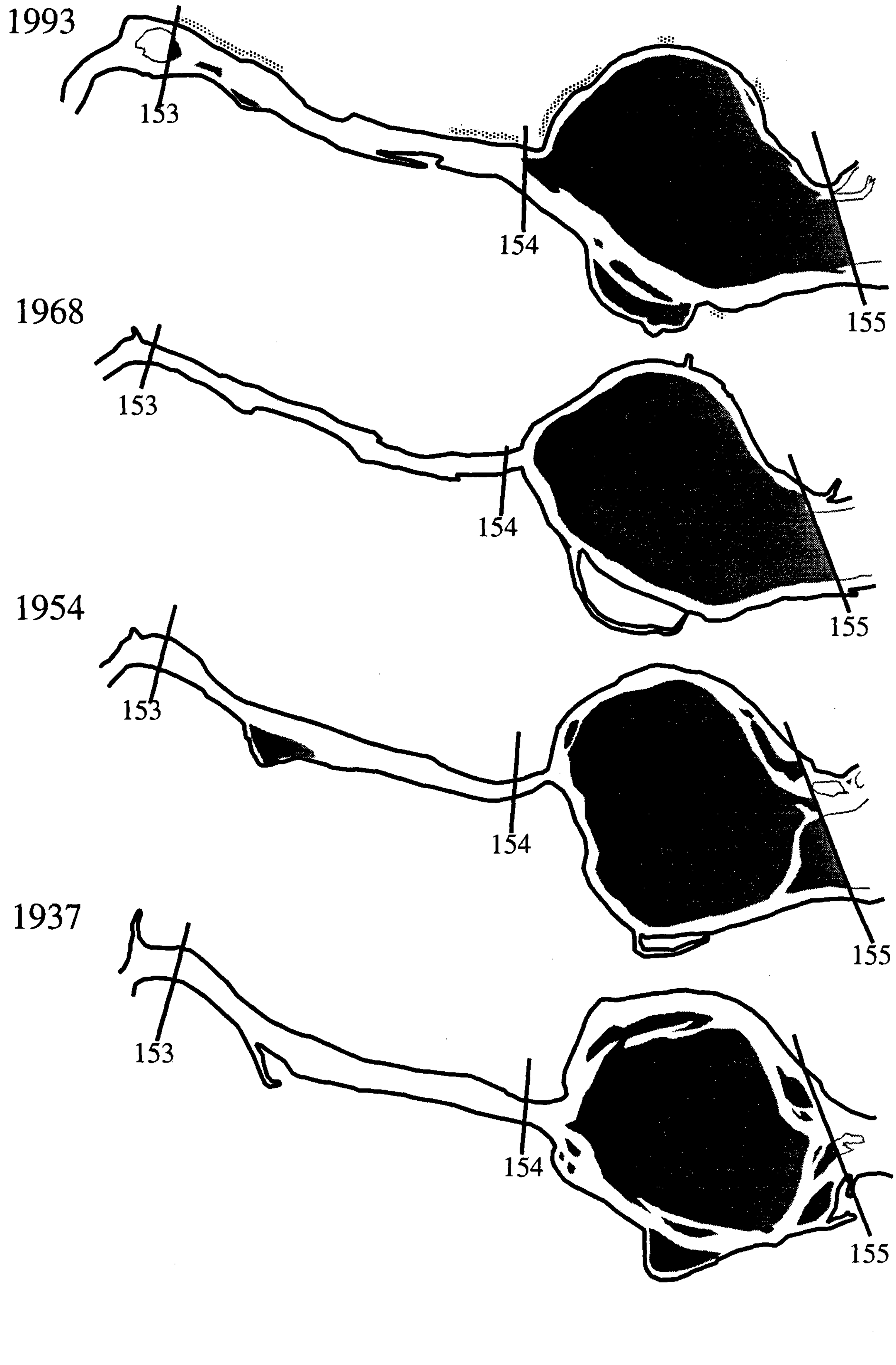
1993
153
154
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1968
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1954
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1937
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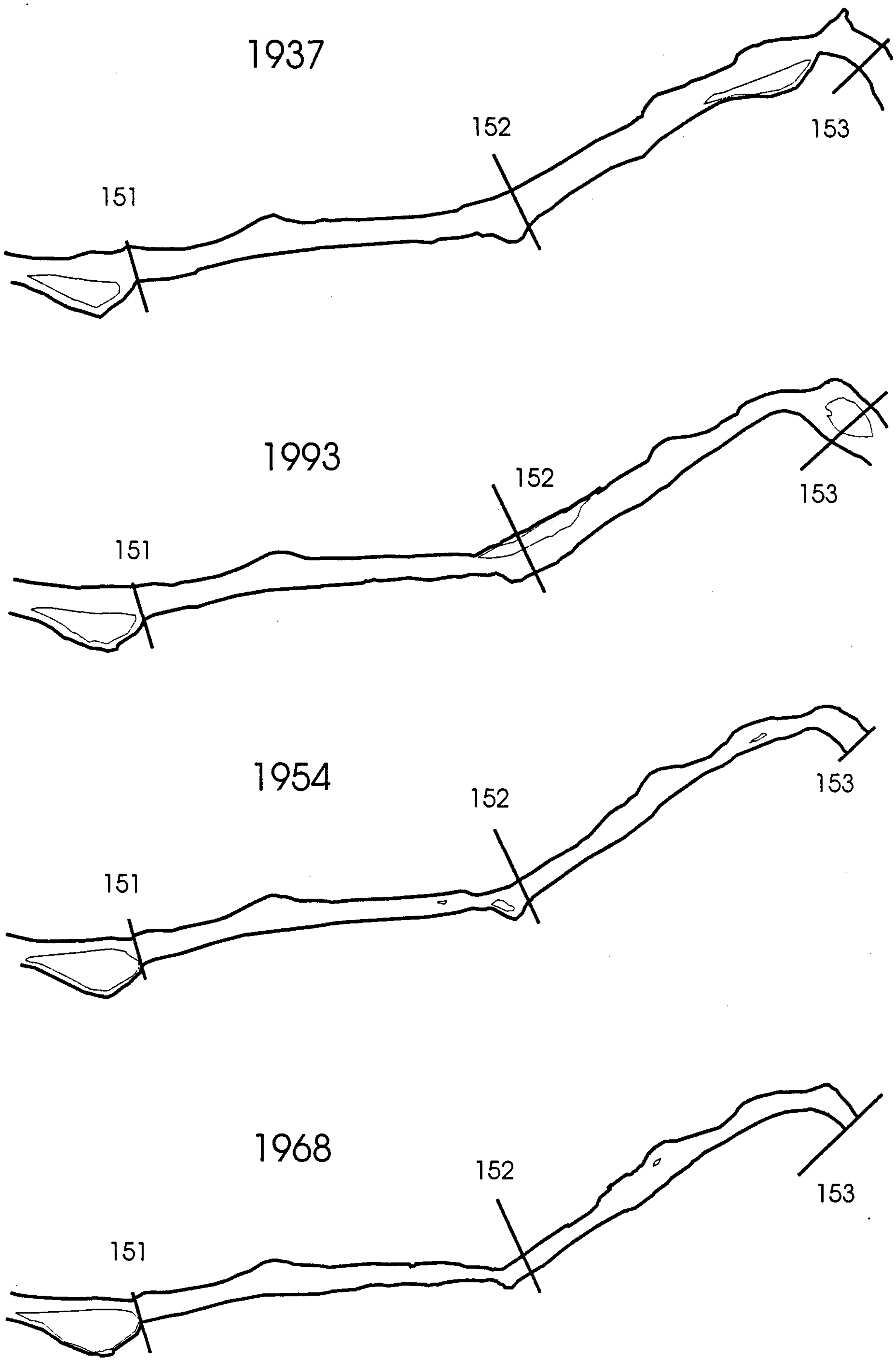
155

Appendix II. Maps of the Ruby-Horsetheif Canyon reach for 1937, 1954, 1968, and 1993.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152
153
151
1993
152
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1954
152
153
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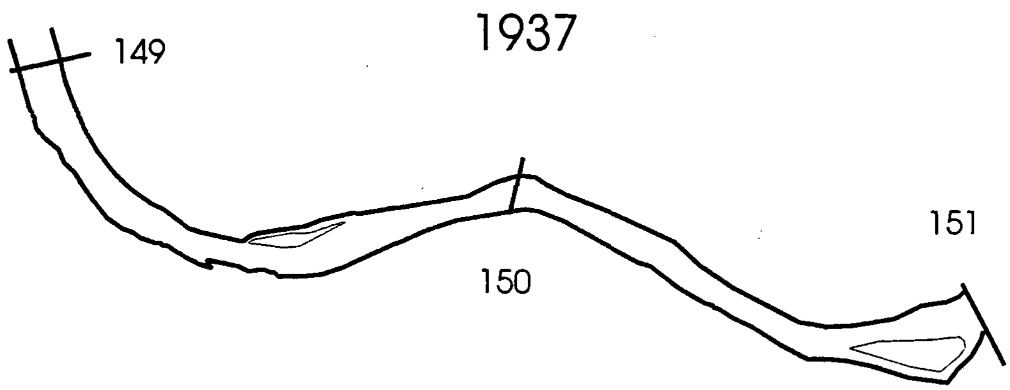
1968
152
153
151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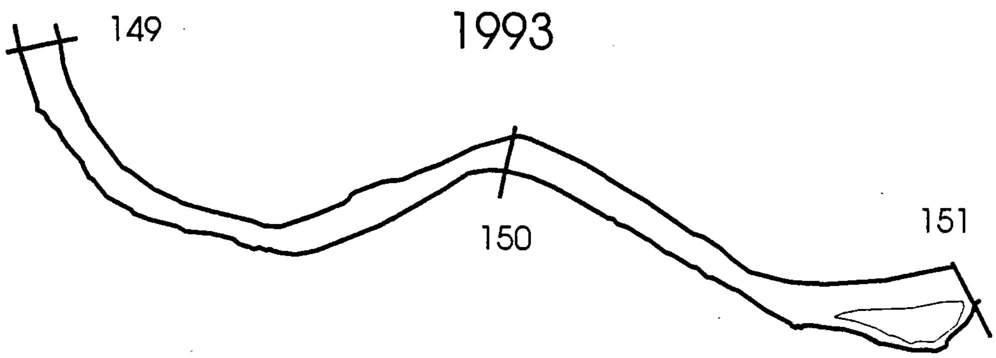
151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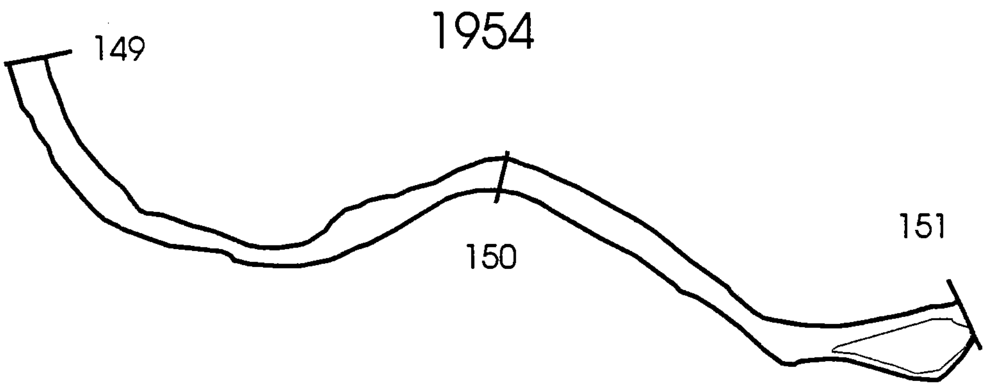
1954
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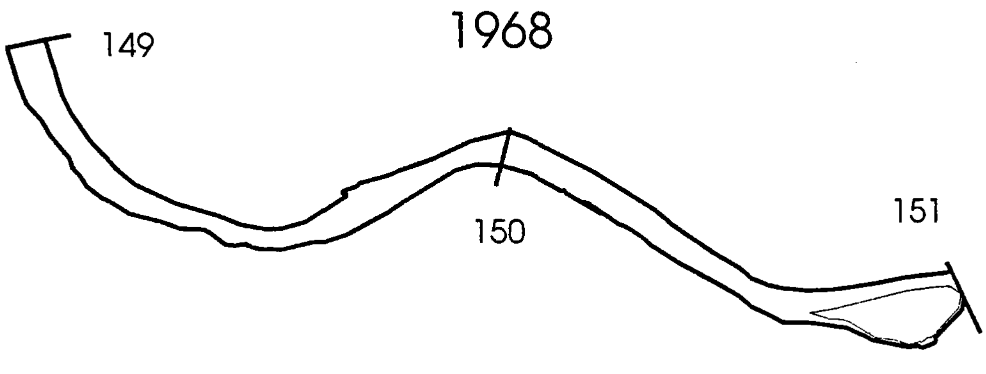
1968
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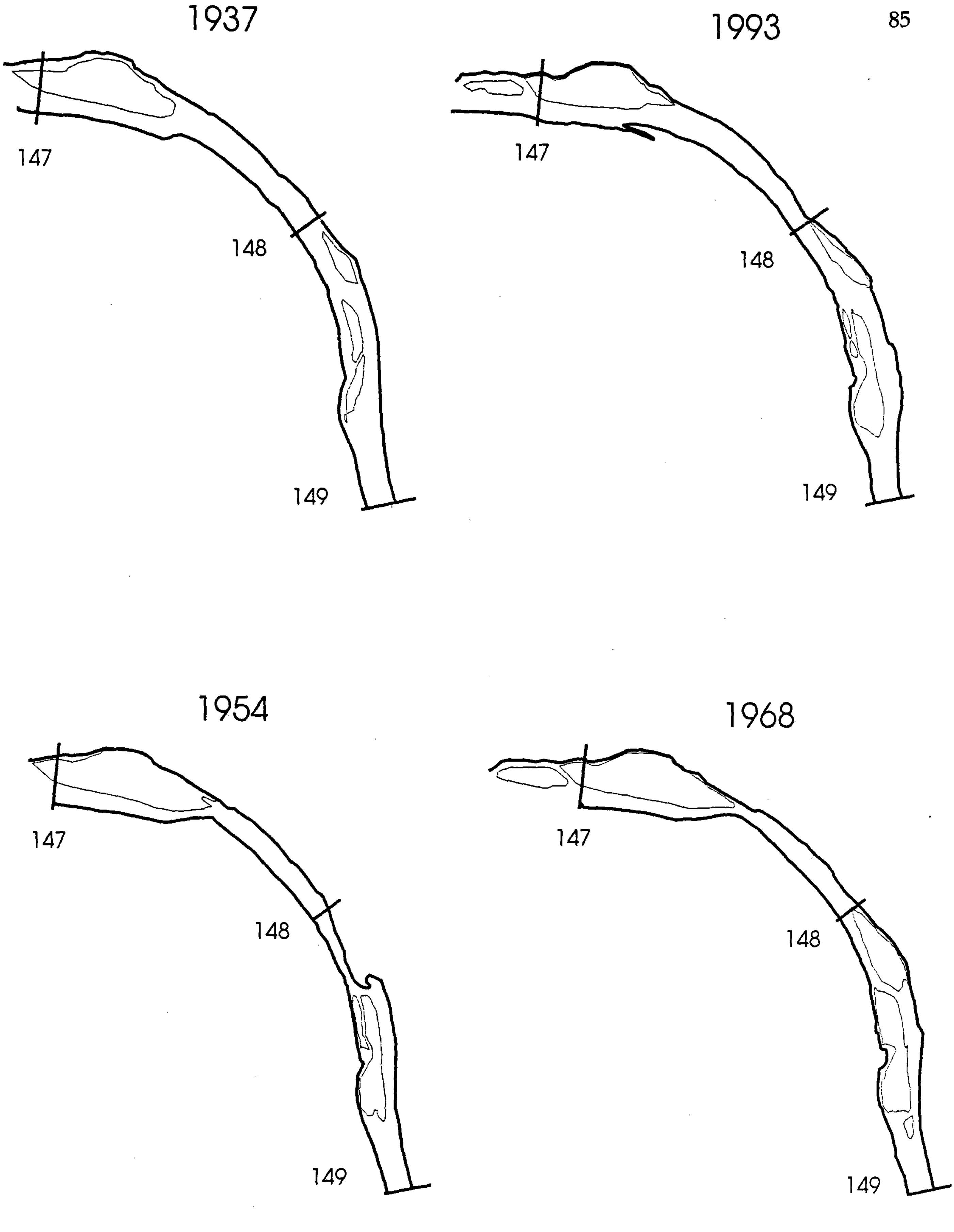
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1993
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1954
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1968
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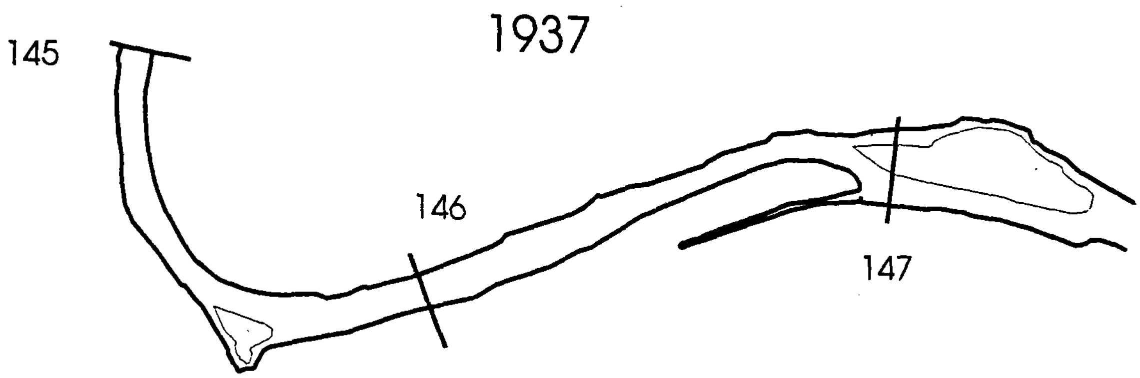
1937
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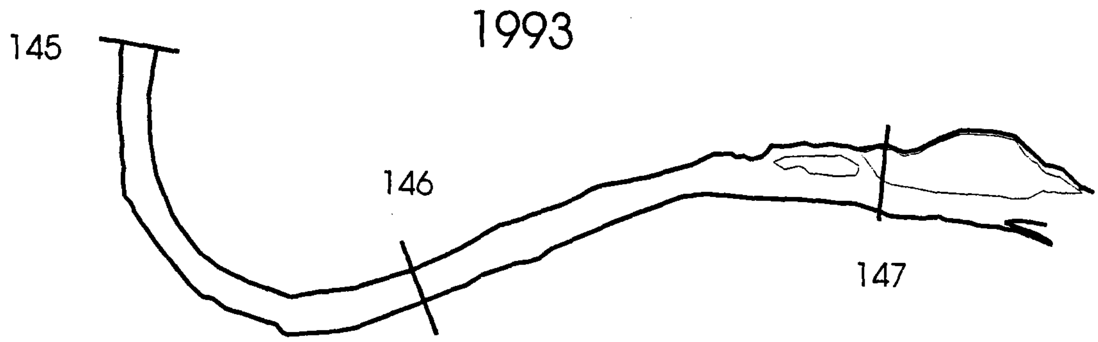
1993
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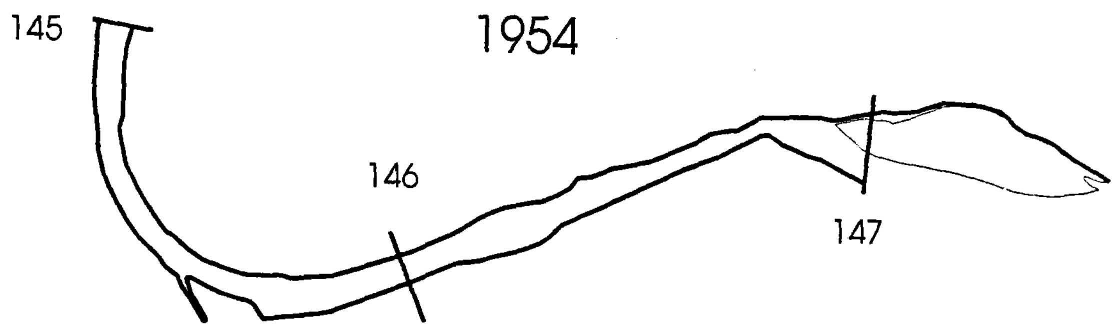
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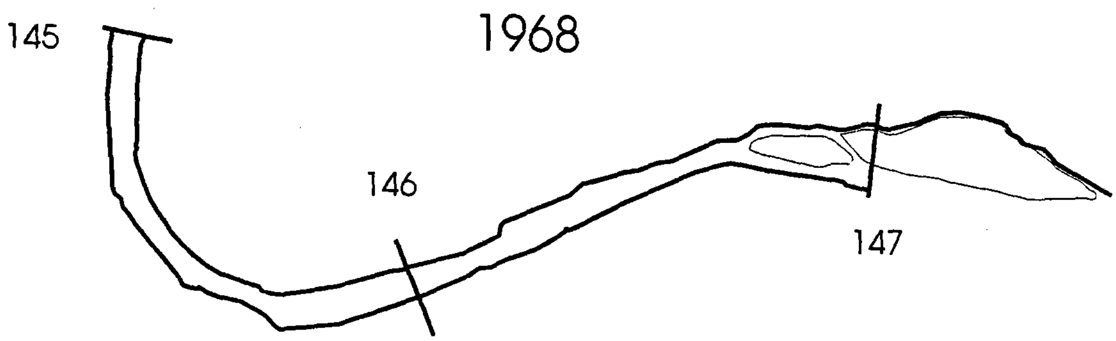
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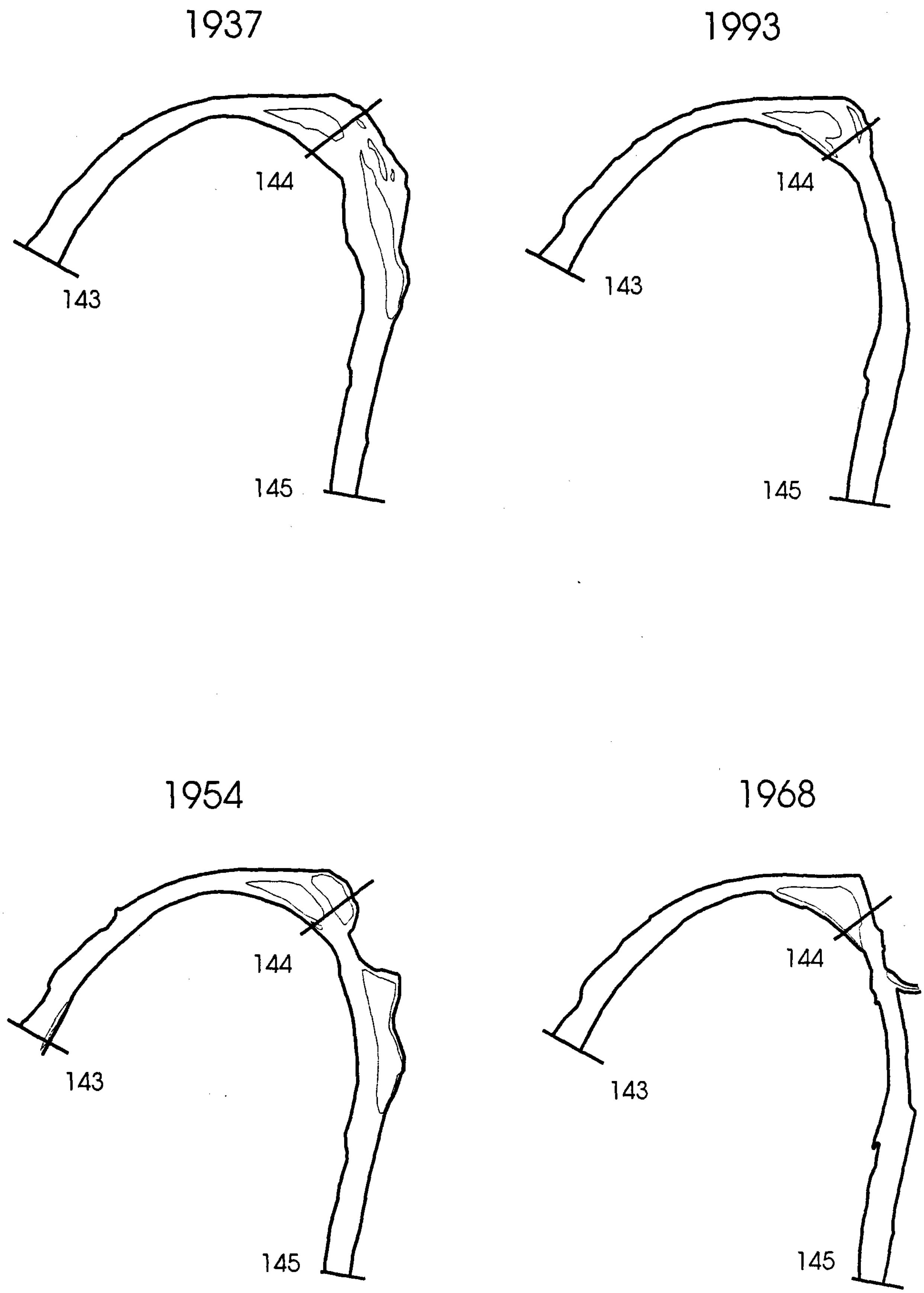
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1954
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1968
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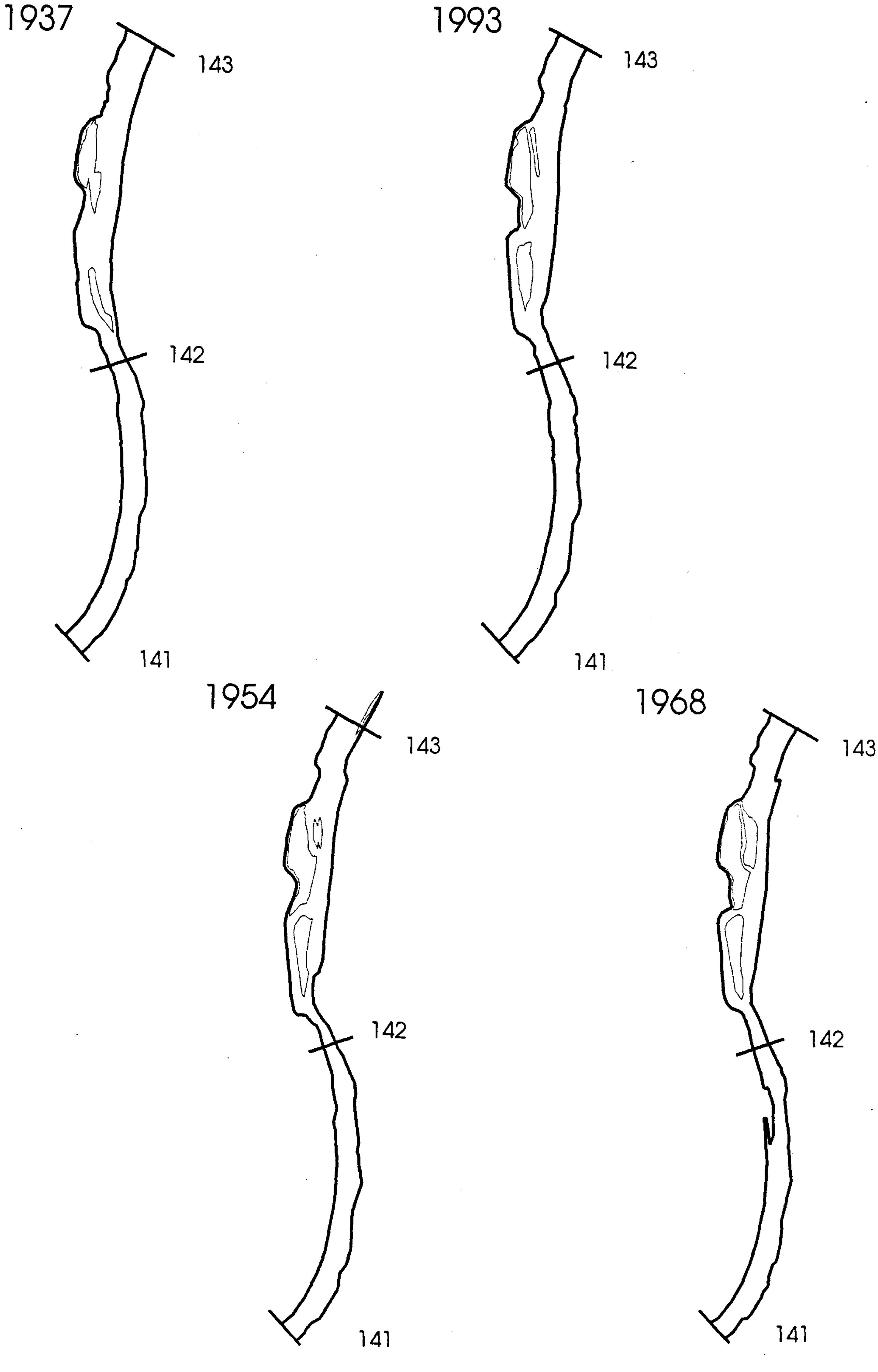
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1954
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1968
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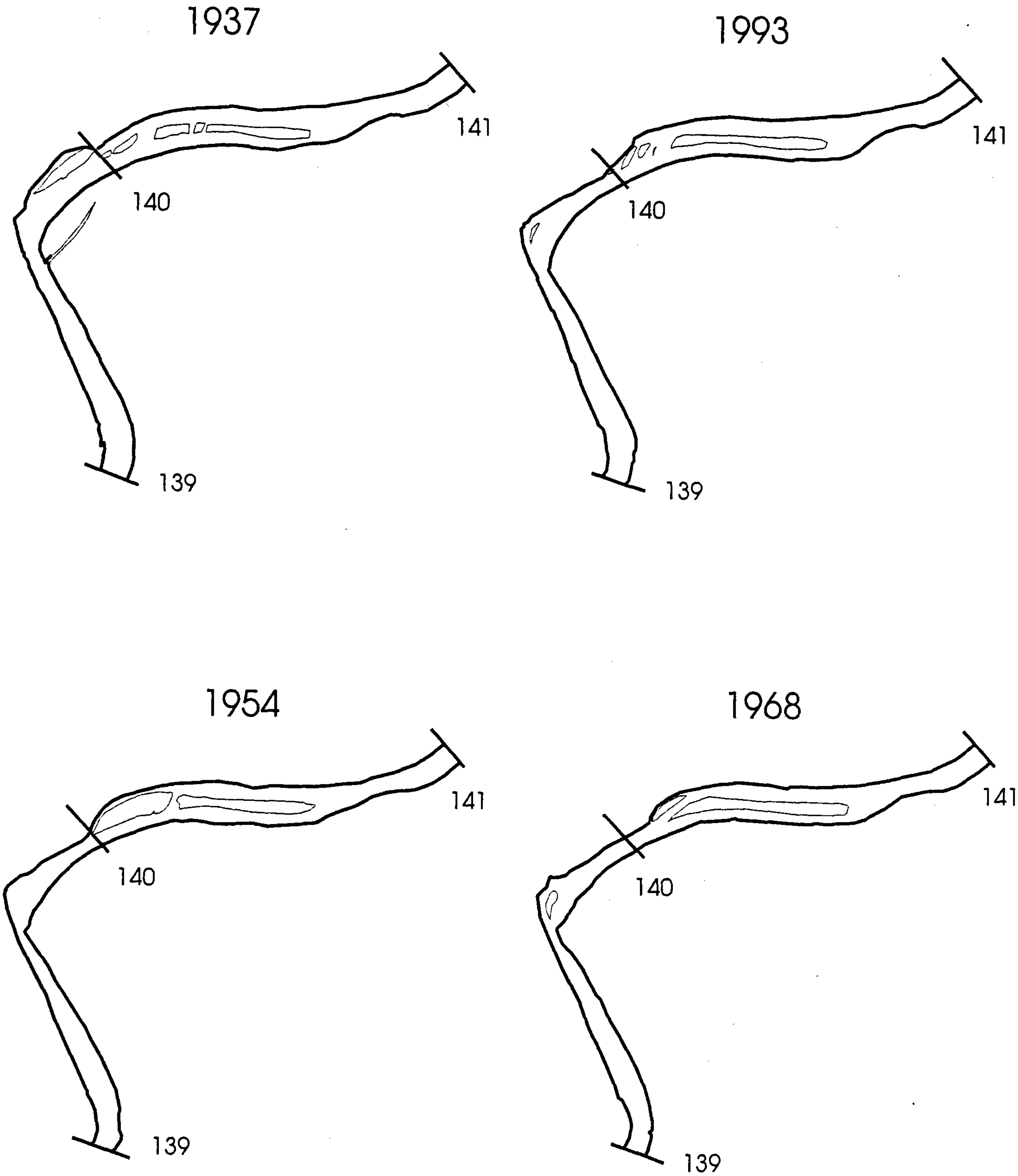
1937
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1993
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1968
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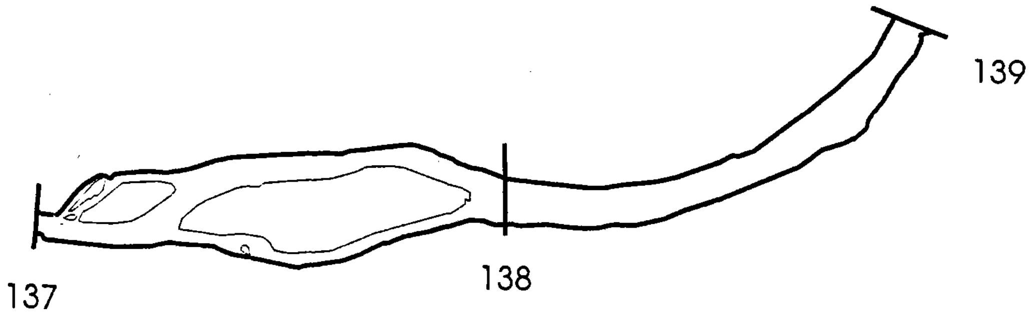
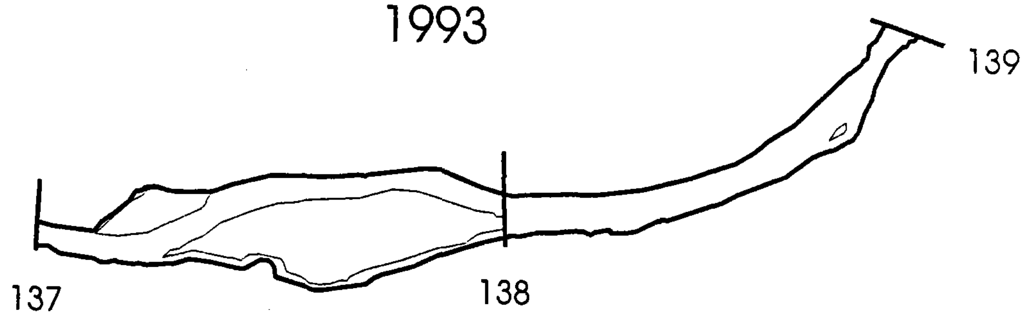
1937



1993



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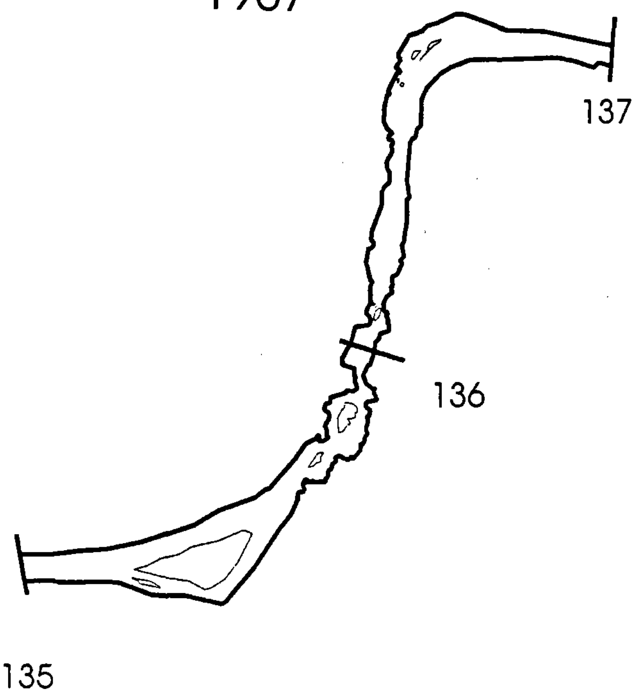

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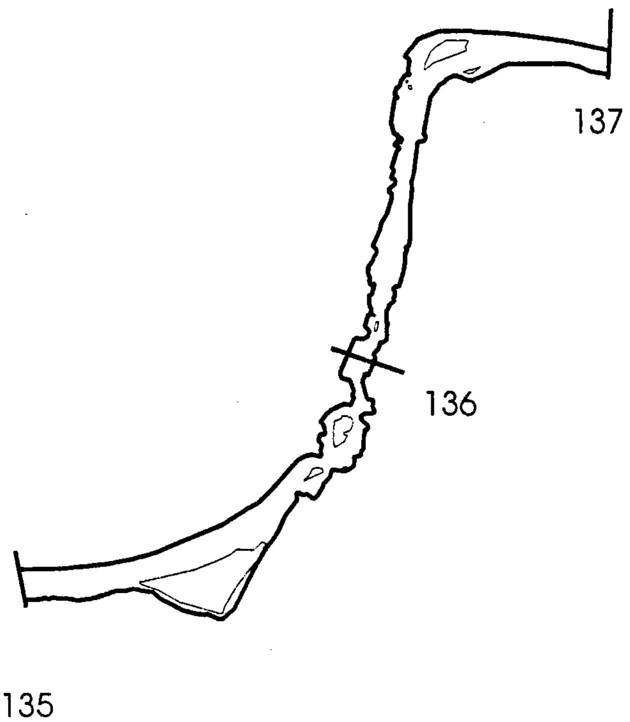

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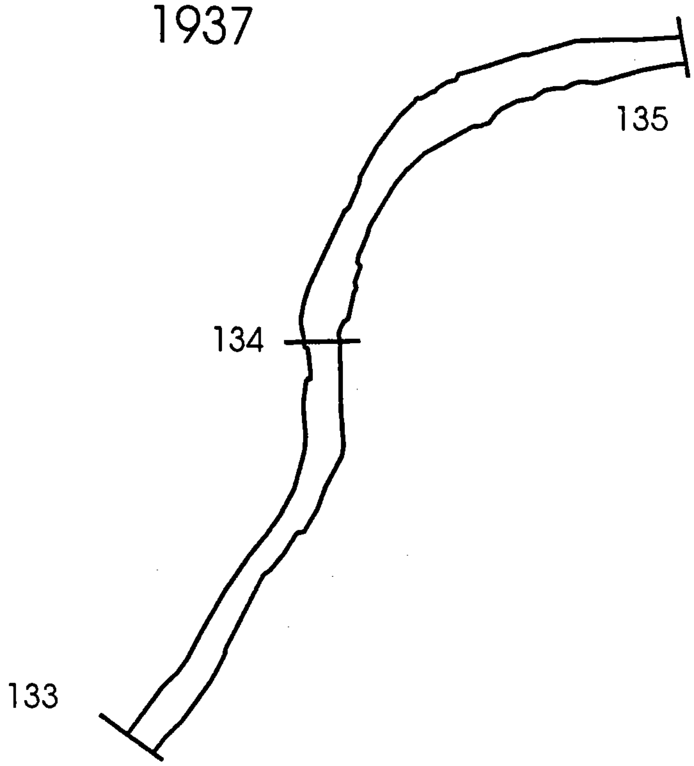

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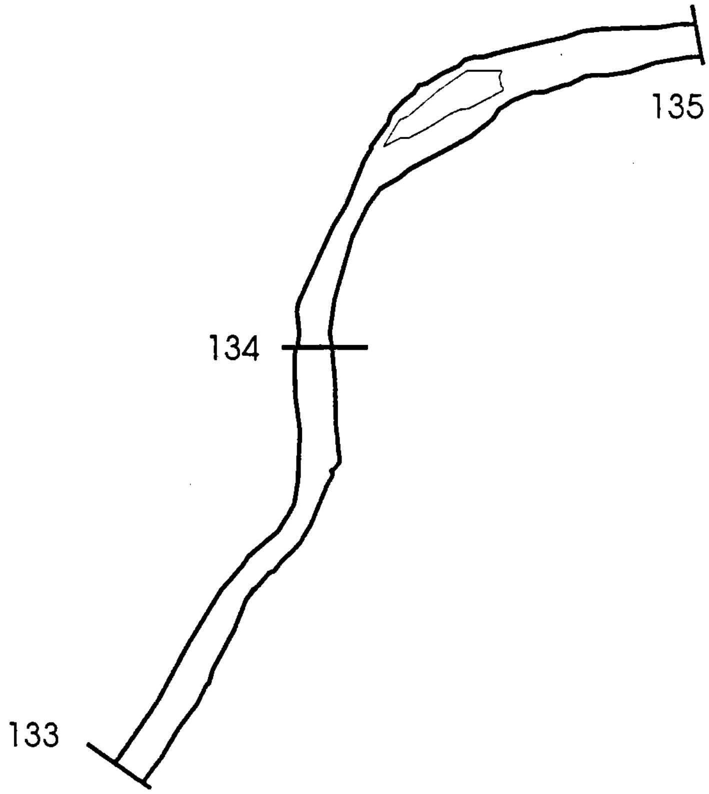

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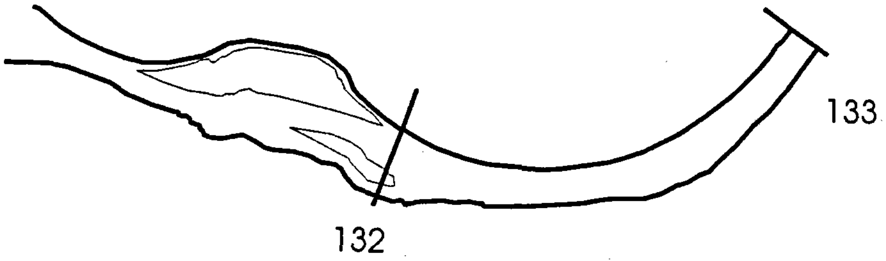

1993