MONITORING THE EFFECTS OF INTERIM FLOWS FROM GLEN CANYON DAM ON SAND BAR DYNAMICS AND CAMPSITE SIZE IN THE COLORADO RIVER CORRIDOR, GRAND CANYON NATIONAL PARK, ARIZONA

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ABSTRACT

The effects of the Interim Flow (IF) discharge regime from Glen Canyon Dam (GCD) on Colorado River sand bars is of particular concern to river managers. An evaluation of sediment resources in eddy systems is critical. This report presents results from a monitoring study designed to evaluate the effectiveness of IF in reducing sand bar degradation and camp site loss.

Biannual topographic and bathymetric survey comparisons at 30 sites indicate that both the amount of sediment and the area available for camping was continued to decrease during the period of IF. Sand has been displaced from the upper elevations of sand bars to the lower elevations of recirculation zones and the main channel. Erosion caused by the river is typically occuring by the development and shoreward migration of cutbanks. Within 12 months after the onset of IF nearly all the reattachment bars had readjusted to the change in flow regime as cutbank migration lowered bar platforms to lower stage elevations. Deposition is occurring in smaller recirculation zones within and below the range of IF stage elevations. This lower elevation deposition perches former high-discharge return channels beyond the influence of IF. Perched channels are effectively disconnected from the river and have filled in with sand, silt, and vegetation. The decrease in return channel area is limiting native fish habitat because these "backwaters" are only viable at certain stage elevations not well represented by IF.

Based on the increase in sediment storage in recirculation zones and the main channel proximal to the sand bars we conclude that the IF are achieving their objective of minimizing sediment transport. However, erosion of the higher elevation portions of sand bars (camping sites, native species habitat, etc.) is continuing, and therefore, "bar-building" flows of powerplant capacity or greater are needed to replace sediments above normal dam operating parameters. Three floods occurred along the Little Colorado River during the winter of 1993 that provided an unexpected test case of the bar-building event by elevating Colorado river stages to slightly higher than powerplant capacity. Downstream of the LCR, bar-top elevations were raised by 1-2 meters of sand bar deposition. High erosion rates ensued upon the return to IF and within 6 months the newly aggraded bars had destabilized to pre-flood size, but high elevation sediment gain remained in higher areas not reached by the IF stage elevations.

These results support the need for bar-building flows as recommended in each of the proposed alternatives in the Glen Canyon Dam Environmental Impact Statement. Sediment accumulated during the IF period can be successfully redistributed during a high-flow release. However, the differences in erosion rates due to various dam operating scenarios should be considered in the design of the flows that follow proposed, dam-controlled habitat restoration floods.

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INTRODUCTION

Overview of Project

The Colorado River is the most highly-regulated river system in North America (Stanford and Ward, 1979) and has the highest proportion of its annual flow stored in reservoirs of any major North American watershed (Hirsch et al., 1990). GCD operations completely control its flow through Grand Canyon (Water Science and Technology Board, 1991). The operational effects of GCD include hydraulic erosion and aggradation and thus affect the stability of fluvial sediment deposits in Lower Glen, Marble, and Grand Canyons (Howard and Dolan, 1981; Beus et al., 1985; Water Science Technology Board, 1987; Schmidt and Graf, 1990; Rubin et al., 1990; Beus and Avery, 1992). The National Park Service recognizes sand bars as a primary natural and recreational resource because they form the foundation on which the fluvial ecosystem is structured, and thus sediment resources below GCD are the first management priority of Grand Canyon National Park (GCNP). Specifically, objectives for sediment management in the GCNP River Management Plan are: 1) to maintain the various morphologic components of temporary sand storage (e.g., sand bar deposits), and 2) to maintain a positive sand balance (U.S. National Park Service, 1989). Starting in August of 1991, a program of reduced maximum flows and reduced fluctuation from GCD, termed Interim Flows (IF), has been implemented. The IF were designed to mitigate the impacts of dam operations on downstream river resources until a Record of Decision (ROD) is delivered by the Secretary of the Interior for the GCD EIS (U.S. Bureau of Reclamation, 1994). Implementation of IF for GCD during the EIS preparation period requires that sediment resource conditions be monitored.

This report presents the results from survey studies designed to monitor the effects of IF on sand bars and campsite size along the Colorado River through the Grand Canyon. These surveys allow us to test the hypothesis that IF will minimize sediment transport and sandbar erosion along the Colorado River through the Grand Canyon. The study of IF during the period of EIS review is important because the EIS Preferred Alternative (EIS-PA) essentially <u>is</u> IF with an additional, yearly bar-building/habitat maintenance flow and endangered aquatic species research flows (U.S. Bureau of Reclamation, 1994). The sand bar study involves the comparison of topographic and bathymetric surveys at 30 sites located in each of the 11 geomorphic reaches of the Colorado River corridor (as defined by Schmidt and Graf, 1990). The campsite size study addresses the carrying capacity of the river corridor by quantifying IF impacts on the size of campsites used by river rafting trips and hikers. To determine the effects of IF on the sediment and recreational resources within Grand Canyon National Park, the following objectives were set.

Objectives

A. Monitor subaerial and subaqueous sand bar topography on an annual to biannual basis at 30 representative sand bars in the Colorado River corridor downstream from GCD during the IF period (Figure 1; Table 1).

B. Examine change in campable area between 1991 (before IF) and 1994 (during IF) as a function of changes in sand bar size and morphology resulting from GCD operations.

C. Determine how unexpected flood flows and sediment input from the Little Colorado River (LCR) tributary during the winter of 1993 affected sand bar size, morphology, and camping area.

D. Use the results from the above objectives to compare topographic change and assess sand bar dynamics, and thus determine whether sand bar deposits have been stabilized by IF criteria and GCNP management objectives for the Colorado River in Grand Canyon are being met.

E. Assist in compilation of the above data for the GCES/NPS Geographic Information System (GIS).

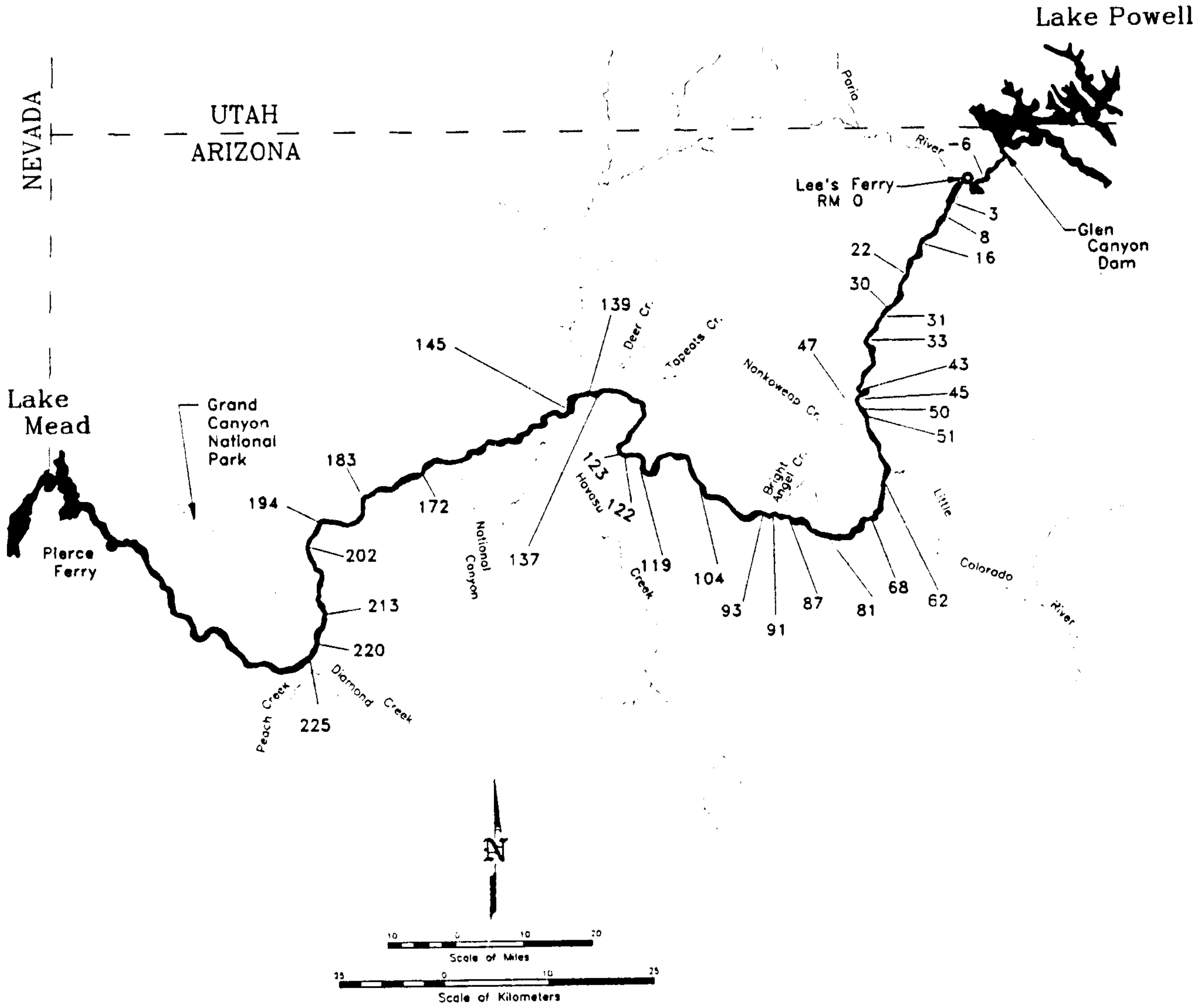


Figure 1. Location map showing study locations

Table 1. Sand Bar Survey Sites*

Site Ref.#	River Mile (RM)	River Side	#	Site Name	Deposit Type
-6	-6.5	Right	2	Hidden Sloughs	R
3	2.6	Left	3		R
8	7.9	Left	4	Lower Jackass	S
16	16.4	Left	5	Hot Na Na	S
22	21.8	Right	6		R
30	30	Right	7	Fence Fault	R
31	31.6	Right	8	South Canyon	S
43	43.1	Left	10	Anasazi Bridge	R/UP
45	45.6	Left	11	Eminence Break	S
47	47.1	Right	12	Lower Saddle	R
50	50	Right	13	Dino	R/S
51	51.2	Left	14		R
62	62.4	Right	34	Dead Chub Eddy	R
68	68.2	Right	15	Upper Tanner	R/UP
81	81.1	Left	16	Grapevine	R/S
87	87.5	Left	17	Cremation	R/UP
91	91.1	Right	18	Upper Trinity	S
93	93.3	Left	19	Upper Granite	R/UP
104	103.9	Right	20	Wanna-be-Ruby	R/UP
119	119.1	Right	21		R
122	122.2	Right	22		R
123	122.7	Left	23	Upper Forster	R/UP
137	136.7	Left	24	Middle Ponchos	R
139	139	Right	25	Upper Fishtail	R/UP
145	145	Left	26		R
172	172.2	Left	27		R
183	182.8	Right	28		R
194	194.1	Left	29		R
202	202	Right	30	202 Mile Cave	S
213	212.9	Left	31	Pumpkin Spring	R/UP
220	219.9	Right	32	Middle Gorilla	R/UP
225	225.3	Right	33	Hell Beach	R

* River Mile #'s from Stevens (1983). Deposit type from Schmidt and Graf (1990): R-reattachment deposit, S - separation deposit, UP - upper pool deposit.

Flow Regimes During Time of Study

The IF have been in effect since August, 1991 (Figure 2) and will continue until a ROD is reached for the GCD-EIS. The IF limit the maximum discharge to 566 m^3/s (20,000 ft^3/s), the minimum to 142 m^3/s (5,000 ft^3/s), with rates of up- and downramp to 57 $m^3/s/hr$ (2,000 $ft^3/s/hr$) and 42.5 $m^3/s/hr$ (1,500 $ft^3/s/hr$), respectively. Daily change cannot exceed 142 m^3/s (5,000 ft^3/s). These IF consist of low-, medium-, and high-volume months, with low flows during the late Spring and late Fall, moderate flows in May and September, and high flows during mid-Summer and mid-Winter.

Natural flood events along the Little Colorado River during January and February, 1993, caused a significant deviation from the lower-volume interim flow regimes along the mainstem Colorado River (Figure 2). Three flood events occurred on the LCR on January 12-16, January 19-23, and February, 23-26, 1993, that raised flows in the mainstem Colorado to 960 m^3/s (34,000 ft^3/s) , 764 m^3/s (27,000 ft^3/s), and 849 m^3/s (30,000 ft^3/s) respectively. Sand was deposited in nearly every eddy downstream of the LCR-Colorado confluence for at least 30 miles, either adding to existing deposits or filling empty eddies. (Hazel et al., 1993).

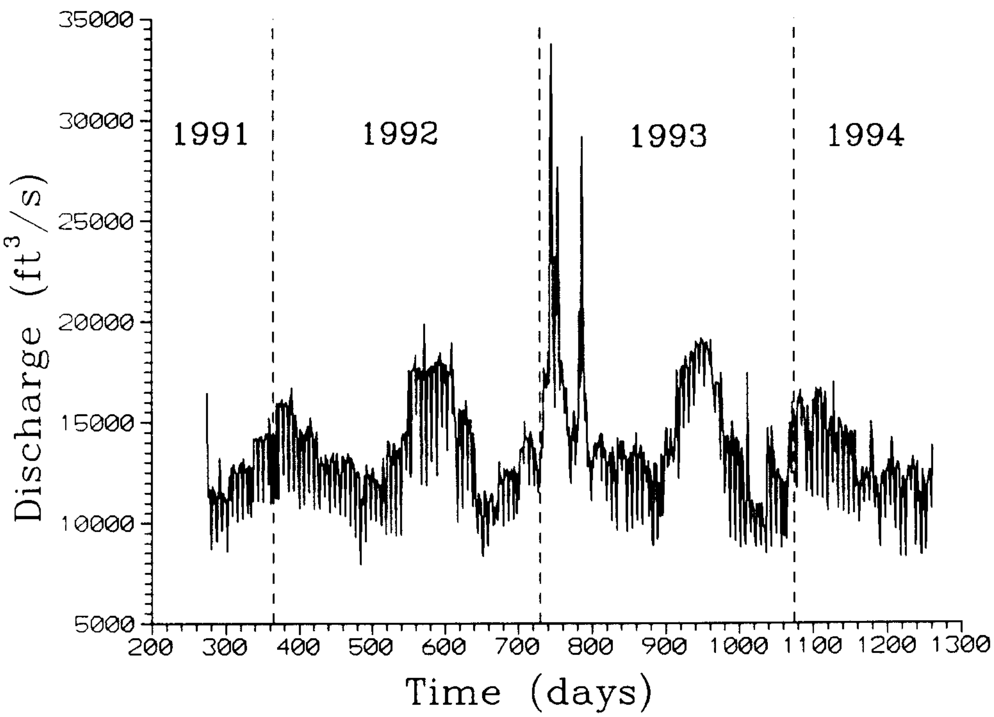


Figure 2. Daily maximum discharge hydrograph from Colorado River guage near Grand Canyon (RM 88) for the interval between October 1991 and June 1994.

The study of IF during the period of EIS review is extremely important because the EIS Preferred Alternative (EIS-PA) essentially is IF with an additional, yearly bar-building/habitat maintenance flow and endangered aquatic species research flows (U.S. Bureau of Reclamation, 1994). The winter floods of 1993 provided an unexpected test-case of a bar-building flow event. Therefore, results from research conducted during IF are directly applicable to the EIS-PA scenario.

Modern Alluvial Deposits Of The Colorado River

Alluvial sand deposits along the Colorado River corridor in Grand Canyon are generally associated with tributary debris fans that form local restrictions and expansions in the main river channel (Figure 3; Webb et al., 1989). Typically these channel irregularities produce a recirculation zone (eddy) where flow separates from and then reattaches to the bank (Schmidt, 1990). Deposits that form in recirculation zones or similiar low-velocity areas in bedrock channel gorges have been described from this and other similiar settings (McKee, 1938; Howard and Dolan, 1981; Baker et al. 1983; Baker, 1984; Schmidt, 1990). Water velocities in recirculation zones are much lower than velocities in the main channel and therefore are sites of potential sand deposition by a variety of bar forms (Schmidt, 1990). Deposition is typically localized near the separation point, reattachment point, and eddy center. Schmidt and Graf (1990) recognized four major types of alluvial sand deposits in Grand Canyon:

reattachment deposits form upstream of the reattachment point of large primary eddies. They are typically formed along the lower, downstream regions of the eddy by currents sweeping across the eddy toward the shore and perpendicular to the main river current. This type of bar is characterized by a broad platform that extends upstream into the eddy. Return current channels form along the shoreward side of the reattachment bar platform where the eddy current is redirected along the shoreline.

separation deposits typically form immediately downstream of debris fans which produce constrictions in the main river channel. They commonly mantle the downstream portion of the debris fan and are deposited in secondary eddies upstream of the larger primary eddy associated with the debris fan. This type of bar is typically steeper and of higher elevation than reattachment bars.

upper pool deposits typically form upstream from debris fans or other constrictions in the main channel within minor recirculation zones. They commonly occur as linear deposits along and parallel to the shoreline.

channel margin deposits are those that parallel the shoreline in areas not specifically related to recirculation zones or separation points.

In addition to the above, *main-channel sediments* are transported and locally deposited along the channel bottom as discontinuous stringers of sand.

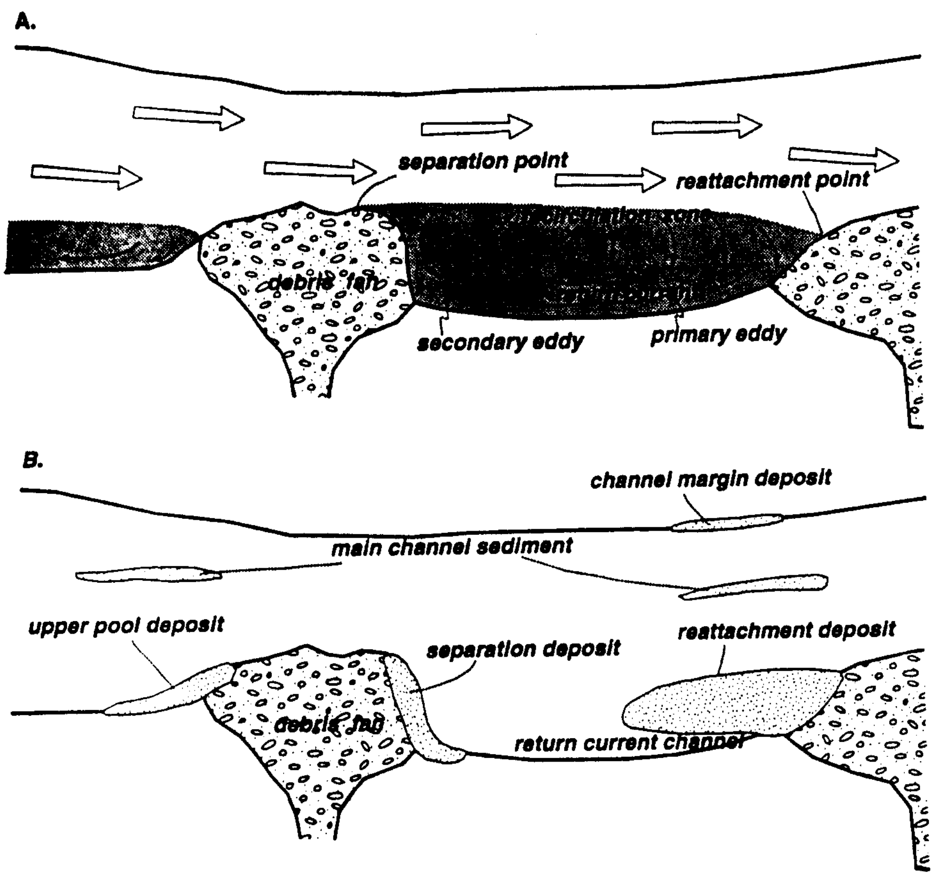


Figure 3. Schematic diagram showing flow patterns and configuration of bed deposits in a typical recirculation zone. A) flow patterns. B) Configuration of bed deposits. Modified from Schmidt and Graf (1990).

Sand storage in recirculation zones varies with changes in discharge, size and dimensions of debris fans, and tributary sand input. Sand is therefore a sensitive indicator of dam operations and consequent cause and effect relationships. Depending on the operating regime for GCD the balance between sand supply and main channel transport can be positive or negative (Smillie, et al., 1992). Since much of the remaining sediment in the Colorado River below GCD is stored in recirculation zones, the effects of IF operations on the stability and morphology of sand bar deposits is closely linked to how recirculation zones respond to alternative water release patterns.

During lower discharge flow regimes such as IF, recirculation zones generally consist of a primary eddy and large areas of both the reattachment and separation bars are exposed. The reattachment deposit may fill much of the recirculation zone beneath the primary eddy. As discharge increases and recirculation zones expand, more area is inundated, and secondary eddies or low velocity zones develop upstream of the return current channel. Return-current channels are excavated by the increase in current velocity as flow across the bar converges with the upstream flow along the channel bank (Rubin et al., 1990). Expansion of the recirculation zone causes the reattachment point to migrate downstream and the separation point to migrate upstream and onto the debris fan. Sediments deposited within the expanded, higher-discharge eddy system are exposed to a very different flow pattern when decreasing discharge shortens the dimensions of the eddy. For example, deposits which were within the high-discharge recirculation zone become subjected to downstream flow as the reattachment point migrates upstream and sand is lost to the main channel (Schmidt and Graf, 1990).

Previous Work

Sand Bars

Until recently knowledge of the downstream effects of GCD in Grand Canyon was based on profile surveys of about 20 sand bars since 1973, and occasional aerial photography since 1965 (Howard, 1975; Howard and Dolan, 1981; Beus et al., 1985; Schmidt, 1990; Schmidt and Graf, 1990). These studies documented slight to insignificant instability of sand bars under the post-dam fluctuating flow regimes, with bar building reported under the high flows of 1983-1986, and both prior and subsequent erosion. Erosional patterns are obscured by variability in reach characteristics, local channel geometry, poorly developed stage/discharge relationships, unknown antecedent conditions, and survey accuracy. Schmidt and Graf (1990) determined that the sand bars monitored by Howard (1975) and Beus et al. (1985) and typically used as campsites were an unusually stable subset of the entire population of sand bars.

Increased public environmental concern led to funding of multidisciplinary research in 1990 (Water Science and Technology Board, 1991) that was coordinated by Glen Canyon Environmental Studies (GCES Phase II) to provide information for the GCD-EIS. As part of this research, the Bureau of Reclamation conducted a series of 11-day test flows in 1990-1991 to determine the impacts of specific flow regimes on sand bar stability (Beus and Avery, 1992). Important sediment studies contained within Beus and Avery (1992) and other investigations conducted as part of the GCES Phase II program that are germane to this report include bank stability changes related to groundwater fluctuations (Carpenter et al., 1991; Budhu, 1992; Werrel et al., 1993), bar deposition rates (Andrews, 1991), modeling of recirculating flow (Nelson, 1991), daily photography detailing short-term topographic changes (Cluer, 1992), repeated surveying of topographic changes (Beus et al., 1992), and analysis of long-term tends in sediment storage (Schmidt et al., 1992).

Budhu (1992) and Werrel et al. (1993) studied seepage erosion, an importantand perhaps dominant erosional mechanism operating in systems with rapid changes in stage elevationn (Howard and McLane, 1988). Seepage-driven erosion occurs when rapid decreases in water level leave perched water tables in cohesionless sediment deposits, such as sand bars along the Colorado River. As the bankstored groundwater drains, it causes rilling and ultimately mass wasting at the water's edge. In Grand Canyon, discharge from GCD may vary up to an order of magnitude during a day. This fluctuating regime creates a "daily tide" from the dam to Lake Mead, Arizona. Under normal dam operations river stage typically drops faster than bank-stored groundwater can drain from the sand bars, leaving a perched water table in the bars, resulting in seepage-driven rilling and mass wasting of over-steepened banks.

In their evaluation of how alternative discharge regimes affect the stability of sand bars Beus and Avery (1992) concluded the following:

1) Sand bar topography was affected by discharge, local geomorphology, sediment supply, and antecedent conditions.

2) The temporal and spatial record of sandbar change must be considered to fully interpret short term measurements of sand bar responses to flow regimes. Periods of low discharge (1966-1982 and 1987-1990) were characterized by aggradation of low elevation sand bars, while high elevation sand bars degraded. Between 1983 and 1986, when annual peak discharges were more than twice the low discharge periods, bars in wide reaches aggraded and bars in narrow, critical reaches were eroded. Erosion rates change through time as a function of changing sediment storage: aggradation rates in 1987-1990 were equivalent to those of 1966-1982, but degradation rates were about twice as great.

3) The total amount of sand bar instability, both aggradational and degradational, was positively correlated with increasing distance downstream from GCD. Bar instability was slightly but not significantly positively correlated with mean discharge, increasing daily fluctuation, and increasing ramping rate.

4) Major periods of erosion followed periods of aggradation suggesting that antecedent conditions influenced subsequent changes in sand bar topography.

5) Periods of aggradation were associated with large-fluctuation flows. However, high-fluctuating flows were also associated with degradation or little net change.

6) Little change or slight net erosion characterized the three constant flows and the low-fluctuation test flows.

7) Bank failure correlates with change from one flow regime to another. Consequently, ramping rate, in particular down-ramping, is suspected as the most destructive component of flow under normal dam operations.

8). Both short- and long-term discharge patterns from Glen Canyon Dam affect the stability of sand bars.

Campsites

Sand bars that have recreational value are called "beaches" and are commonly used as campsites (U.S. National Park Service, 1989). Three campsite inventories conducted between Lees Ferry (RM0) and Diamond Creek (RM226) show a decrease in the number of campsites between 1973 and 1991. The first inventory, in 1973, documented 333 campsites above river fluctuations 708 m3/s) (Weeden et al., 1975). The second inventory was conducted in 1983 after flood level flows were discharged from the Glen Canyon Dam; it documented 438 campsites. The increased number of campsites since 1973 was primarily attributed to the previous year's flood releases (Brian and Thomas 1984). The most recent survey, which was not preceded by flood conditions, was conducted in 1991. This inventory documented 226 campsites, a 32% reduction in campsite number since 1973, and a 48% reduction since 1983 (Kearsley and Warren, 1993). A comparison of the three inventories also shows an overall decrease in size of campsites. Size class (small, medium, large) comparison of 133 campsites documented in all three inventories shows that 41% of the campsites had decreased in size class between 1973 and 1991, while only 5% had increased in size class.

SAND BAR STUDY

Study Sites

We have collected topographic and bathymetric measurements from up to 34 sand bar study sites along the Colorado River corridor during four river survey expeditions: October 15-November 3, 1992, April 1-15, 1993, October 7-28, 1993 and April 7-18, 1994 (Figure 1; Table 1; Appendix A). The April, 1993 trip was initiated to examine sand bar response to winter flood events and resulting sand input from the LCR tributary (RM61). In addition to topographic surveying, sedimentologic data was aquired from trenching flood and pre-flood deposits. Our data set also includes surveys conducted after 1 to 2 months of interim flow operations, during October and November, 1991 (Table 2).

Methods

Field surveys during IF were conducted bi-annually during low-discharge months in the Spring and Fall on 15-20 day river trips. The trips consisted of two ground-based survey teams, a bathymetry team, and a sedimentology/stratigraphy team. Each ground-based team completed one survey per day using Leitz Set4c and Set3c instruments equipped with data collectors. Bathymetry crews collected data at two sites each day. A total of thirty sites are included in our database, however, not all sites were sampled during every research trip (Table 2: Appendix A).

A variety of bathymetric survey techniques were used during the course of this study. Initially (1991), bathymetric surveys were conducted using a Lowrance X-16 depthfinder mounted on the raft. Sonar profiles were located by attaching one end of a metered cable to the transducer mount on the boat and locating a survey assistant with a cable/reel system on the sand bar at a surveyed point. Two points along the beach were marked and used to guide the boat along the proper azimuth. Distances from the cable operators location to the boat were recorded every two meters and corresponded to fiducial marks on the analog sonar recording. Coordinates of individual depth and distance were obtained by calculating the offsets along the azimuth of the profile based on the surveyed location of the cable reel

Table 2. Interim Flow Sand Bar Surveys

		July 1991		September 1991		October 1991		October 1992		April 1993		October 1993		April 1994	
Site (Mile)	Deposit Type	Vol m^3	Area m^2	Vol m^3	Area m^2	Vol m^3	Area m^2	Vol m^3	Area m^2	Vol m^3	Area m^2	Vol m^3	Area m^2	Vol m^3	Area m^2
-6R	R	3388	3523					3331	3645	3370	3516	3338	3470	3276	3585
3L	R	3564	3016			2640	2467	4052	3601	3995	3448	3061	2401	3417	3130
8L	S	1351	1482			1316	1524	1354	1729	1408	1788	1301	1440	1286	1403
16L	S	1726	1284					2103	1549			1316	981	1386	1122
22R	R	3578	1727			3197	1474	3276	1593	3532	1819	2012	4008	3930	1994
30R	R	7366	3656							5662	3377	3708	2379	3969	2922
31R	S	2055	2407	2013	2400	1936	2298	2033	2884	2124	3333	1740	2130	1806	2315
43L	R/UP	3661	2107	3629	1903	3610	1959	3453	1844	3285	1723	3380	1744	3616	1974
45L	S	3456	2585	3549	2656			3119	2479			2498	3121	3133	2550
47R	R	7647	7180					5790	5923			5761	6078	5313	5273
50R	S/R	3921	2452					2390	1952	2394	2099	2782	2475	2732	2547
51L	R	6441	5939	6422	5830	6463	5789	6109	5519	6029	5596	4511	4093	5136	4981
68R	S/R/UP	3723	3077	3410	2658	3426	2818	3171	2979	2390	2102	6341	4828	5496	4106
81L	R/S/UP	2811	1334	2520	1184	2515	1154	2431	1223	2766	1249	2567	1198	2485	1180
87L	UP	492	317	521	323			607	395	596	571	593	414	605	414
91R	S	241	223	169	139	171	135	189	208	216	155	171	126	180	161
93L	UP/R	1634	1401	1256	1021			1888	1690	2145	1717	2057	1590	2224	1878
104R	UP/R	526	364					504	360			428	289	426	311
119R	R	4825	2792	3645	2291			2481	1724	3952	2360	3192	2011	2767	2252
122R	R	4928	3622			4900	3568	4435	3134	5666	2990	5120	2860	4908	3004
123L	R/UP	1310	1280					1223	1317			1160	1118	825	954
137L	R	4989	2924	4116	3018	4189	2965	3965	2994	4074	2879	2976	3712	3761	3074
145L	R	928	582	833	540	838	510	756	496	1046	570	933	549	916	544
172L	R/UP	2448	2254	1327	1068	1340	1120	1719	1415	1535	1105	1043	878	1367	1591
183R	R/UP	2670	2077	2694	2152			2905	2237	4723	2710	4180	2436	4023	2476
194L	R/UP	4357	3284	4387	4262	3296	4388	4464	3377	4823	3287	5005	3451	4765	3363
202R	S	3710	2230					3075	1981	2991	1768	2295	1611	2133	1617
213L	R/UP	2772	1334					3625	1693	3781	1520	2802	1398	2814	1514
220R	S/UP	1190	717	1069	719			1035	719	1266	742	953	665	1032	712

* R-Reattachment Bar; S-Separation Bar; UP-Upper Pool (from Schmidt and Graf, 1990).

operator. Elevations of the bathymetry points were calculated by subtracting the sonar depths from the surveyed water's edge elevation. The sonar equipment was calibrated daily to control changes in the travel time of the signal due to suspended sediment load. The extent of areal coverage generated from this technique was limited to the region directly in front of the sand bar face and to the 45m length of the metered cable. On the October, 1992 survey trip we employed a different bathymetric survey system that allowed us to expand our coverage to include the entire river channel surrounding the sand bar. This system consisted of the Lowrance depthfinder mounted on the boat and a total station located at a known shore location and is referred to by the nickname "hardly-hydro". The location of the boat was determined by targeting a reflective prism mounted directly above the transducer. The analog sonar recording was marked each time a position was aquired, typically every 7-10 seconds. The sonar records were then digitized at every mark and the elevation of the bathymetry points were obtained by subtracting the digitized depths and distance between the target and the transducer from the elevation collected by the total station. Following the October, 1992 survey trip using the "hardly-hydro" system, the GCES survey division purchased the "hydrographics Survey Package" (HSP) that automates the entire data collection process and collects highly accurate digital data. The HSP has been utilized on every trip since then and consists of a shore total station and a boat-mounted transducer and computer to control the data collection. The shore station data is radio-telemmetred to the boat computer where depth-position data is calculated and automatically stored. A comparison of the different methods is planned for September, 1994 in order to determine the relative differences between the methods.

Survey protocol was developed during the GCES Phase II test flows (see Beus et al., 1992) and documented according to standard survey practices for ground surveying. Benchmark and backsight relationships were verified at all sites during March, 1991. Upon completion of each survey, field data were transferred to micro-computers and edited.

The ground-based and bathymetric survey points are then combined and used to form a Triangulated Irregular Network (TIN) model of the surface. Following the methods of Beus et al. (1992), we have prepared topographic maps of the sites with a 0.2 m contour interval, constructed profiles across the deposits, and calculated the sediment volume and area within what we term the "hydrologically active zone" (HAZ), that portion of the sand bar exposed to the range of dam operations (142-850 m^3/s). In addition, area beneath selected cross-sections will be calculated for the hydrologically inactive zone (HIZ) outside the range of dam operations, the HAZ, and the bathymetric zone. The percent change in volumes and areas will be analyzed using a multivariate analysis of variance against the last pre-interim flow survey data.

Results

Sediment Volume Within the HAZ

Surveys conducted shortly after the onset of interim flows show a system-wide negative response of sandbar HAZ to the new discharge pattern (Table 3; Appendix A: volume versus time plots). After 14 months of low and high volume interim flows the response was as follows: of the 29 sand bars evaluated, 66 % (19) lost sediment volume within the HAZ, 17% (5) gained volume, and 17% (5) remained the same as compared to volumes calculated from the survey previous to the onset of interim flows (Table 3). Among the different deposit types sampled, reattachment bars showed the most significant HAZ volume increases (Appendix A: RM 2.6, 87, 93), while separation deposits showed the most volume loss (Appendix A: RM 45, 50, 202). HAZ volume was increased in reattachment bars by deposition below the maximum interim flow stage elevation, particularly along the upstream portion of the bar platform.

The surveys conducted in April, 1993 included 24 sand bars (Table 2) and examined the effects of the Jan/Feb 1993 flood events from the LCR drainage. Not suprisingly, we measured a significant increase in the movement and volume of sand bars downstream of the LCR (Figure 4, Table 3). Eight sand bars were examined above the confluence of the Colorado and LCR to examine changes in the more sediment-starved portion of the

Colorado River and the possible influence of sediment input from the Paria River (RM 0.5). 63% (5) remained relatively unchanged between October, 1992 and April, 1993, 25% (2) had a large volume gain (RM 22, 31), and 13% (1), RM 43, sustained a significant net loss of HAZ sand (Table 3). Downstream from the LCR and Colorado River confluence, 16 sand bars were examined, including a new reattachment deposit at RM 62.4 in a recirculation zone previously devoid of a significant subaerial deposit. 73% (11) showed large volume increases (e.g., RM 81, 183), 20% (3) remained relatively unchanged (RM 87, 137, 202), and 2 (17%) lost HAZ volume (RM 68, 172) as compared to the October, 1992 surveys (Table 3). The response of sand bars above the LCR was similiar to the aforementioned sand bar response to interim flow operations between August 1, 1991 and October, 1992. Sand bars below the LCR showed large volume gains. Post-flood erosion, however, was quickly destabilizing the bars to pre-flood volumes (Figure 4, RM 202).

Table 3. HAZ Volume Changes

8/91 to 10/92	INCREASE	DECREASE	SAME
ALL SITES Percent (number) n=29	17% (5)	66% (19)	17% (5)
SITES ABOVE THE LCR n=12	17% (2)	58% (7)	25% (3)
SITES BELOW THE LCR n=17	18% (3)	70% (12)	12% (2)

10/92 to 4/93			
ALL SITES n=23	52% (12)	13% (3)	35% (8)
SITES ABOVE THE LCR n=8	25% (2)	12% (1)	63% (5)
SITES BELOW THE LCR n=15	73% (10)	13% (2)	20% (3)

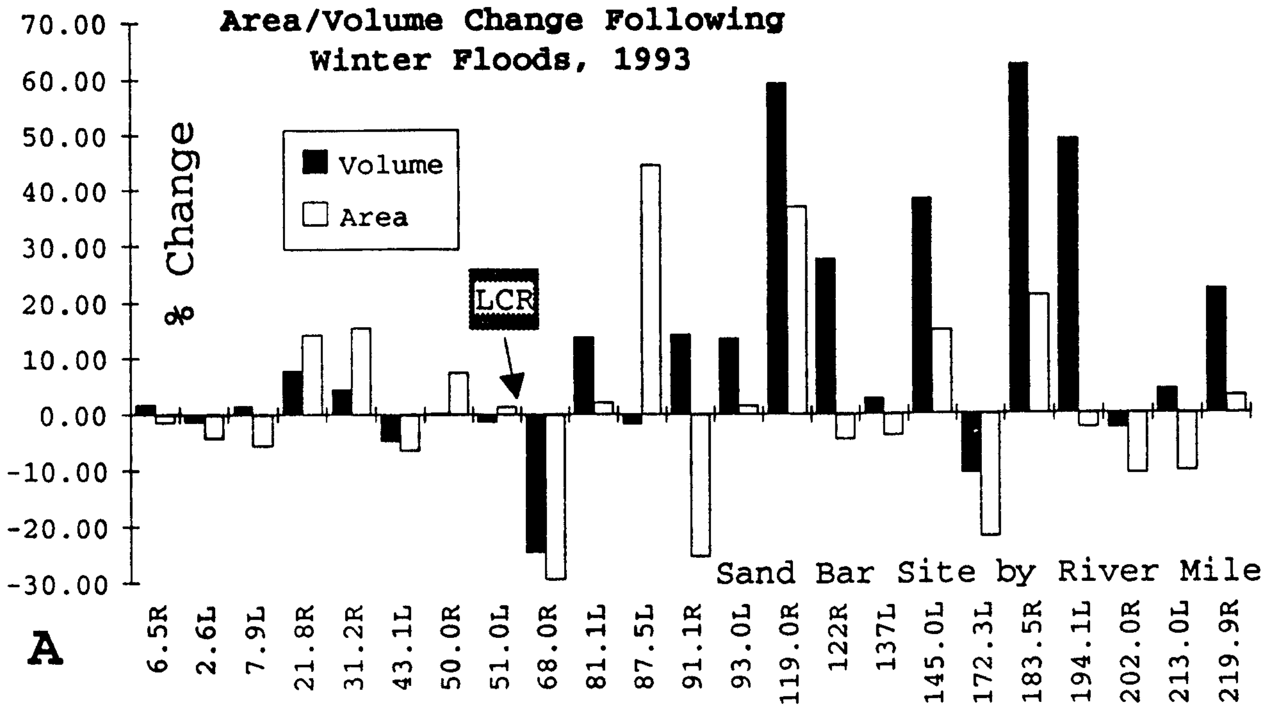
4/93* to 10/93			
ALL SITES n=29	17% (5)	66% (19)	17% (5)
SITES ABOVE THE LCR n=12	25% (3)	50% (6)	25% (3)
SITES BELOW THE LCR n=17	12% (2)	77% (13)	12% (2)

*10/92 used for comparison on sites that were not surveyed on the April trip

10/93 to 4/94

ALL SITES n=29	35% (10)	21% (6)	45% (13)
SITES ABOVE THE LCR n=12	42% (12)	08% (1)	50% (6)
SITES BELOW THE LCR n=17	29% (5)	29% (5)	41% (7)

Although erosion rates decreased between April, 1993 and October, 1993 many of the bars have degraded to pre-flood volumes and several still appeared to be unstable. 77% (13) of the bars below the LCR decreased in HAZ volume (Table 3). This is not surprising as newly aggraded bars are expected to erode, however, 50% (6) of the bars between GCD and the LCR continued to erode or lost the moderate low-elevation volume increase gained since the onset of interim flows (Tables 3). In the 25 month period between the start of interim flows and the October, 1993 survey 62% (18) of the sand bars continued net degradation, while 24% (7) aggraded and 14% (4) remained the same (14%).



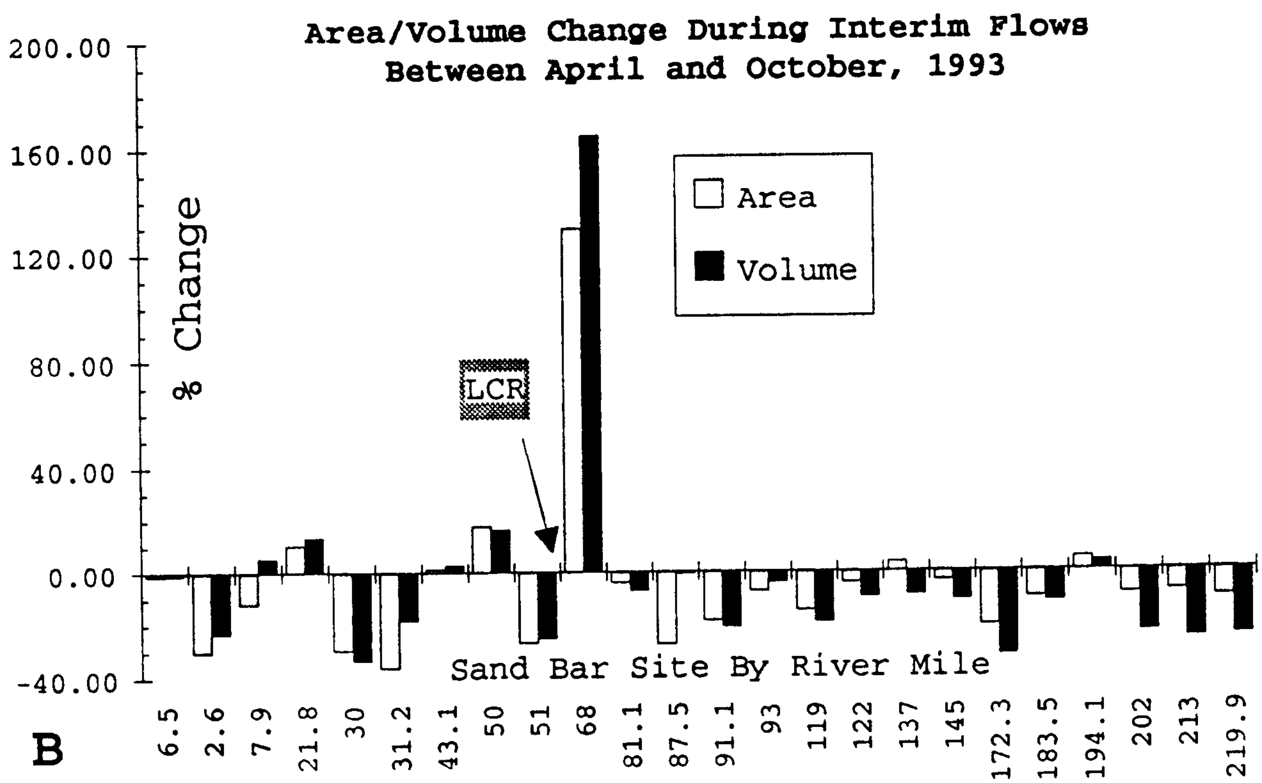


Figure 4. Net HAZ volume and area change for A) 23 sand bars between the October 1992 and April 1993 surveys; and B) sand bar volume and area change between April and October 1993. Note the dynamic sand bar response to the floods downstream from the LCR in A and loss of HAZ volume in these same bars in B.

Sand Bar Profiles

Appendix A contains profiles for all sand bars studied that demonstrate several relationships inferred from the HAZ volume analysis. Low-level flow fluctuations have resulted in erosion of the upper portion of nearly all bars by the development and subsequent shoreward migration of cut banks (e.g. Appendix A: RM50, profiles 7 &9; RM81, profile 5; RM22, profile 3). The bases of nearly all cutbanks examined were developed at the discharge elevation of the interim flow high fluctuation. As a result, several of the reattachment bars examined in this report decreased in platform elevation by .5 to 1.5 m, prior to the January and February, 1993 winter floods. However, aggradation is occurring along reattachment bar platforms within and below the range of interim flow stage elevations (Appendix A: RM23, profiles 0 & 1; RM2.6) that is resulting in significant HAZ volume increases. This aggradation is occurring on the slope into the main channel on the upstream end of reattachment bar platforms. Deposition within recirculation zones also includes sediment in-filling of eddy return channels (Appendix A: RM22.8, profile 0; RM2.6, profiles 5 & 6) as aggradation on the platform side of the return-current channel is causing the channels to become narrower and shallower. In addition, return-current channels that occupied the area inundated by 566-793 m^3/s (20,000-28,000 ft^3/s) flows have been abandoned by the smaller interim flow recirculation zones and have been plugged with sand and silt. Obviously, sediment lost from higher elevations cannot be replaced by interim flows because of their lower stage elevations.

The winter floods, however, deposited large amounts of high-elevation sediment (Appendix A: RM122; RM 183). Large-scale cut bank retreat began shortly after the flooding events receded and the newly reformed bars were exposed to fluctuating flows (Appendix A: RM81; RM122, profile 6; RM183, profiles 3 & 5; RM 87). Notice that the sediment-laden floods did not restructure or deflate in-filled return channels (Appendix A: RM183, profile 2). Subaqueous to low-elevation subaerial sediment storage in both recirculation zones and channel areas was substantially increased immediately downstream from the LCR (Appendix A: RM 62; RM 68; RM 87; RM93). However, there was a trend of sand depletion from river-storage downstream of RM 119 (Appendix A: RM119; RM122, profile 3; RM183). It appears that much of the high-elevation sand bar aggradation was at the expense of the modest sand accumulations that had been increasing as a result of interim flows (Compare surveys prior to flood in Appendix A: RM122; RM183). Although eddy scour, typically at lower sand bar elevations, occurred at several of the study bars (RM 119 & 122), high-elevation aggradation was substantial enough to offset a volume loss that would be reflected in our HAZ analysis. Large-scale cut bank retreat, however, was resulting in a rapid reduction in HAZ area (Figure 4; Appendix A: RM 68, 91, 122, 172.

The bathymetric data from the October 1993 and April 1994 surveys provide insights as to the status of sand that was dumped into the mainstem by the LCR. It appears that much of the sand mass is still stored in the 30 mile zone downstream from the LCR (Appendix A: RM68; RM87; RM93). Slight to moderate increase in bed elevation (1-2 m) in the channel adjacent to recirculation zones at several sites occurred during this period, downstream from this zone (Appendix A: RM123; RM137; RM183, profile 7; RM194). This relatively rapid short term sediment storage increase on the riverbed was coincident with HAZ depletion in recirculation zones (Figure 4b). In addition, two large HAZ volume losses (see volume plots in Appendix A: RM 2.6; RM51) are probably the result of bar failure (Appendix A: RM2.6, profile 6).

Structure and Evolution of the "Crash Canyon" (RM 62.4) Sand Bar

A sand bar deposited during the January and February 1993 flood events provided a unique opportunity to examine the rate and style of sand bar development (Kaplinski et al., 1994). The sand bar formed in a channel expansion approximately two kilometers downstream of the confluence of the Colorado and the LCR (Appendix A:62R; Figure 1). This eddy was devoid of a subaerially exposed sand deposit before the flood events. River stages were elevated up to 2 meters above typical fluctuating-flow regime levels at the peak of the flood (Figure 5). After the floods receded, a steep, 1.5-meter high cutbank developed across the face of the bar, exposing the internal structure along the entire 120-meter face of the bar platform. At this site we conducted topographic and bathymetric surveys, sampled paleocurrent directions and sedimentary structuresat marked locations both along the cutbank and at pits dug along the bar top, and collected photographs (Figure 6). A line drawing of the observed stratigraphic relationships was made from a photo mosaic along the face of the cutbank. Based on these data an interpretive model of the sand bar evolution was constructed.

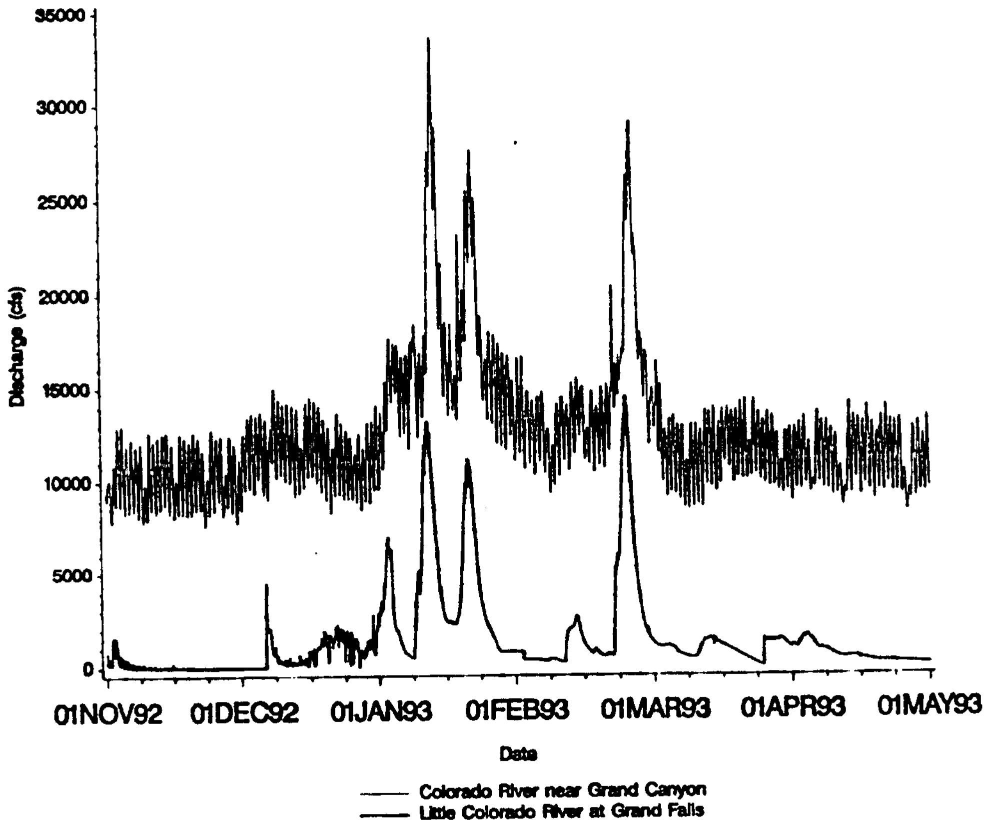


Figure 5. Hydrograph from the Colorado River (RM 88) and the Little Colorado River at Grand Falls for the interval between the October, 1992 and April, 1993.

sand bar evolution. Sedimentary structures exposed along this cutbank suggest that deposition began near the center of the eddy. The structures during this first stage are mainly overlapping scour pits filled with trough-shaped sets of cross-beds caused by subaqueous dunes migrating onshore. Continued deposition, accompanied by migration of ripples, caused the bar to expand until it approached the water surface throughout most of the eddy.

The sand bar was deposited entirely during the three flood events. The majority of the bar was deposited during the first, and largest of the three floods. The bar is comprised of three main stratigraphic units (Figure 6). Initial deposition (Unit 1) began during the first tributary flood event on January 12, 1993. As the flood elevated river stage and delivered large amounts of sediment, large-scale bedforms migrated into and across the empty eddy system accompanied by climbing ripple structures adjacent to the debris fan. The migration of the large-scale bedforms deposited an overlapping sequence of scour pits filled with trough-shaped sets of cross-beds (Rubin, 1987). This style of deposition continued until dune height approached the water surface. The majority of these bedforms were located near the center of the eddy and underly the topographically highest portion of the bar. The second unit was comprised mainly of climbing ripple structures that migrated onshore and onlap the upstream portion of the central core (unit 1) of the bar. Unit 3 overlies both units 1 & 2 and is characterized by horizontal plane beds at the downstream end of the bar that changed laterally into small-scale trough cross beds at the upstream portion of the bar platform. Unit 3 represented the final phase of deposition within the eddy and was the result of bedforms migrating bankward into the the eddy return current channel (Rubin et al., 1990). Units 2 and 3 could either be the product of the second or third flood events or the result of changes in flow regime due to daily dam fluctuations. Although inconclusive, we prefer the latter explanation, especially in reference to unit 2, because of the lack of clearly defined erosional scour surfaces. In addition, stage elevations during the second and third flood events were not as high and may have only slightly overtopped the first flood bar platform. The two later floods do appear to have aggraded the lower-elevation, upstream portion of the bar platform.

style and rates of aggradation and degradation. Following the winter floods and the return to "normal" low-volume interim flow regimes (227-350 m^3/s), erosion rates at the bar increased as the unstable cutbank retreated. This was likely due to migration of the reattachment point upstream because of the lower discharge. The downstream ends of reattachment bars are then subjected to erosive downstream flow (Schmidt and Graf, 1990). An additional increase in erosion rate was observed in June, upon the increase to high-volume interim flow operations (400-556 m^3/s). By mid-July, 1993, the subaerial portion of the deposit that we examined was almost entirely removed. Topographic and bathymetric surveys were conducted in May, 1993 and October, 1993. Comparison of the surveys provides an estimate of the rates of erosion as well as the minimum amount of sediment delivered to the recirculation zone during the sediment-laden floods (Figure 7).

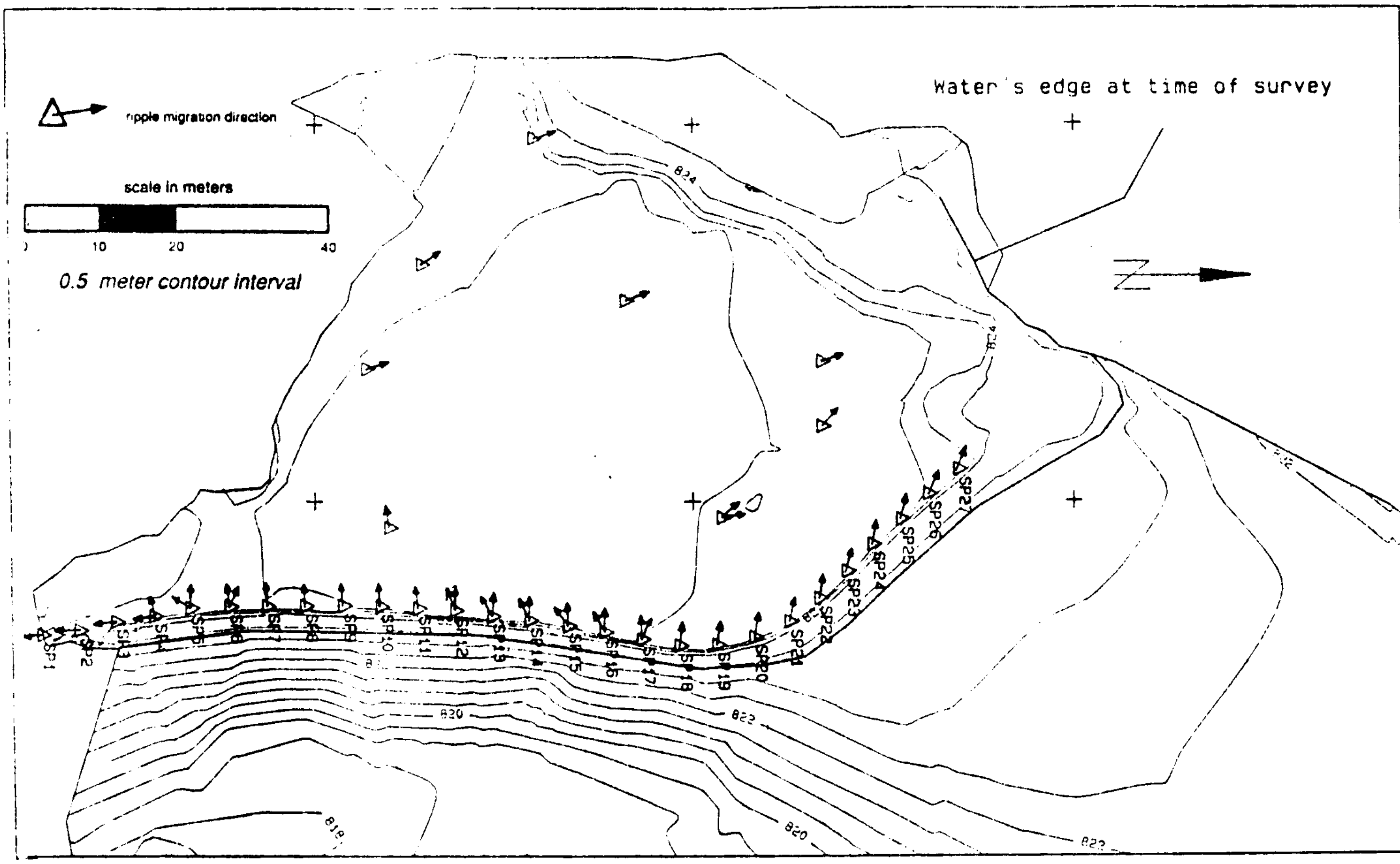


Figure 6. a) Topographic map of study site showing sedimentologic sampling locations. b) Schematic cross section (SP1 to SP27) of the reattachment bar.

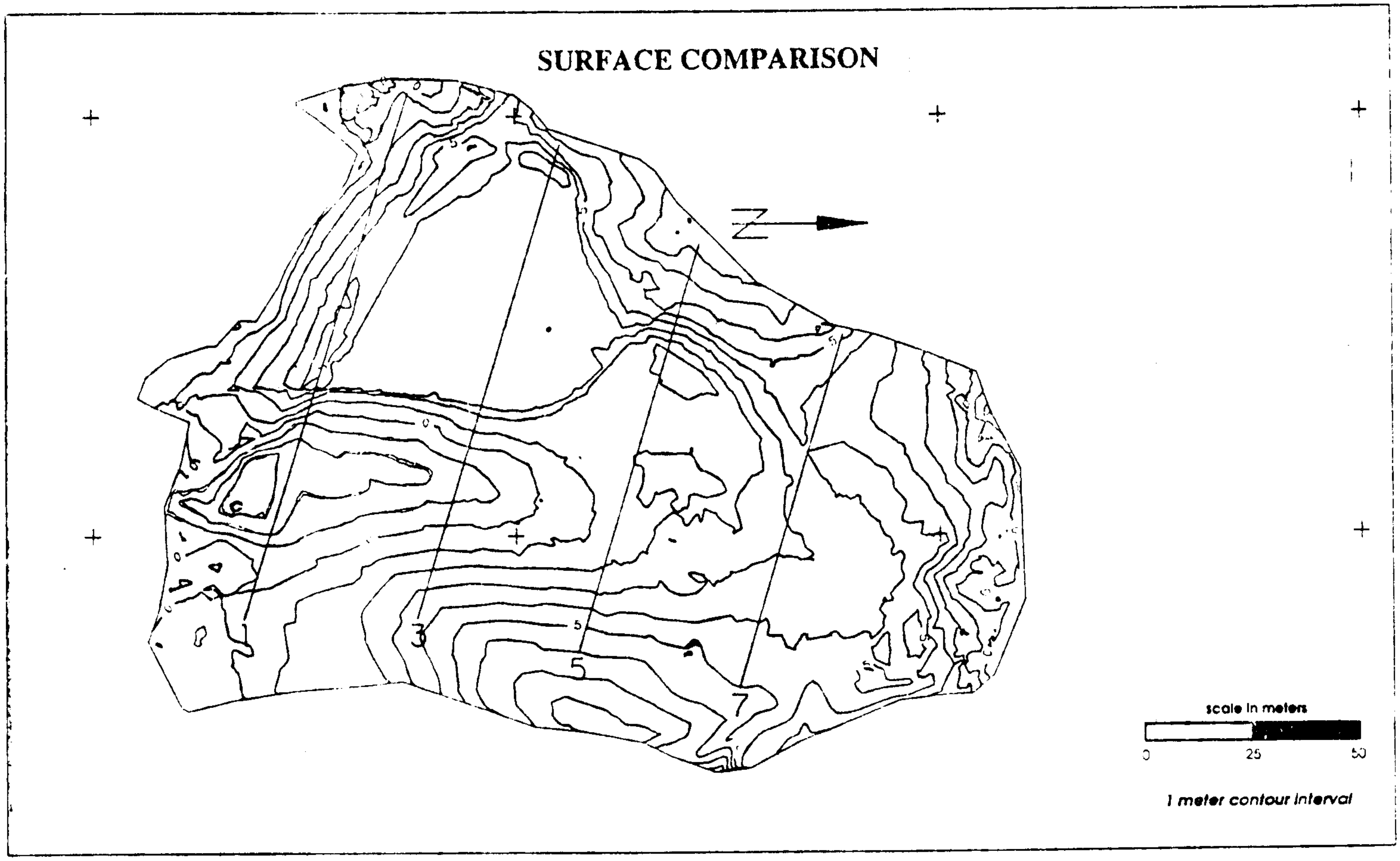


Figure 7. Map of the 62R site with one meter contours of the difference between surveys conducted on 4/5/93 and 10/13/93.

comparison of the surveys show that in the recirculation zone, sediment was removed from the downstream portion of the eddy near the debris fan and from the return current channel. Observations of the site in mid-June, 1993, during low-volume, interim flow operations (230 to 340 m^3/s [8,000 to 12,000 ft^3/s]) showed that only about 5-10% of the deposit we measured in April had been eroded and erosion rates ranged from 50 to 100 m^3/day. An order of magnitude increase in the erosion rates took place on July 1, when dam operation changed to high-volume, interim flow operations (340 to 540 m^3/day [12,000 to 19,000 ft^3/s]). After the change in dam operations we observed that the portion of the bar above the 142 m^3/s (5,000 ft^3/s) stage elevation had completely eroded within a two to three week period. This equates to erosion rates of up to 2,000 to 2,500 m^3/day during this period of time. Therefore, at this site in particular, changes in dam release schedules had a dramatic effect on erosion rates.

The volume of sediment removed from the eddy during this period can also be used to estimate an accurate, minimum volume and rate of sediment accumulation in the recirculation zone during the January, 1993 flood. The actual volume of sediment was probably greater because the eddy system was devoid of a significant deposit prior to the flood event. Sedimentary structures observed along the front of the bar and photographs taken on January 13th indicate that the majority of bar-building occurred during the first flood event, possibly within the several hour period of peak discharge (Kaplinski et al., 1994). Table 4 contains deposition rates calculated for several different periods of time. A total volume of 64,644 m^3 and a sediment density of 2.65 g/cm^3 was assumed in the calcualtions. Assuming that the majority of deposition occurred during the first 12 hours of the flood, our rates are slightly higher than the range of rates (0.22 to 0.05 kg/s) determined from flume experiments of recirculation zone sedimentation (Schmidt et al., 1993). Because of close proximity to the sediment source (LCR), observed high current velocities within the recirculation zone, and the lack of a significant deposit before the flood, this bar may not be representative of eddy dynamics at other sand bars along the river corridor during similar flood events. However, the topographic changes and sedimentologic characteristics at the RM 62.4 site are similar to conceptual models of bar-building in Grand Canyon recirculation zones (Rubin et al., 1990; Schmidt and Graf, 1990; Schmidt et al., 1993). Similar studies should be conducted at other sites with varying geomorphic controls in order to gain a more complete understanding of the response of Colorado River sand bars to flood events.

Table 4. Deposition rates at RM 62.4 during January 12-16 flood

Duration (Hours)	6	12	24	48
Deposition Rate (m^3/s)	10,774	5,387	2,694	1,347
(kg/s)	0.79	0.40	0.20	0.10

Sand Bar Hypsometry

A hypsometric analysis of the 62R was developed as a pilot study to determine the applicability of the technique to the other study sites (Appendix A:62R). The recirculation zone at the 62R site lacked an exposed deposit before the 1993 floods. Following the floods, the eddy was completely filled with sediment. Analysis of this eddy system before and after the flood provide constraints on the range of sediment distribution expected to occur within an eddy system.

Hypsometry is an easily calculated, relatively simple technique that analyzes the distribution of area and elevation within a given region (Strahler, 1952; Schumm, 1956; Bloom, 1991). In this application, we apply a hypsometric analysis to individual recirculation zones along the Colorado River. At each eddy, the area enclosed by .5 meter contour lines is summed for each survey (Appendix A: 62R). By using dimensionless parameters, hypsometric curves can be used to compare different regions, irrespective of true scale. The final report for this study will contain an analysis comparing hypsometric curves and area distribution from the other survey sites.

Comparison of Colorado river recirculation zone area distribution describes the changing condition of fluvial sand deposits. The amount and distribution of sediment within an eddy has an important influence on the sediment flux between the recirculation zone and the main river channel (Beus and Avery, 1992). Describing the antecedent conditions of a recirculation zone through hypsometric anlysis may prove to be an important predictive tool in determining where sediment may be deposited. Experimental flood flows from Glen Canyon Dam are scheduled in the Spring of 1995 that will provide a test of this hypothesis.

CAMPSITE SIZE STUDY

A primary influence of GCD on downstream recreation in Grand Canyon National Park has been its effect on sand deposits (described in the previous section), many of which are used as campsites. The size and abundance of these sand deposits limit the river's recreational carrying capacity, which is of great concern to river users and resource managers alike. Without open sand deposits, river trips could not be conducted because the remainder of the shoreline is too rocky or too densely vegetated to be used as campsites except under extreme circumstances. Development of dam operating criteria must be based on sound understanding of how dams affect downstream resources and activities, including recreation.

The annual number of people traveling downstream on the river through the park increased from 547 in 1965 to 16,428 in 1973 (Shelby, 1981). The National Park Service presently limits use to approximately 22,000 people per year. Even with this limitation, many campsites are used nearly every night during the summer and sometimes, for lack of alternative camps, by two river parties on the same night. Therefore, the status of campsite carrying capacity needs to be monitored during the period of EIS review. The purpose of this study is to examine changes in campsite area and causative factors since the initiation in August 1991 of IF.

Study Sites

Certain reaches of the river are limited in the number of available campsites, and competition for sites in these "critical reaches" is greater than for sites on other stretches of the river (Kearsley and Warren 1993). Critical reaches are RM 11-40.8, 75.6-116, and 131-164. Critical reaches correspond closely to the narrow reaches of Schmidt and Graf's (1990) reach-length classification of the river corridor. Because of their importance to the overall carrying capacity of the river, campsites in critical reaches received primary focus in the 1991 study.

Methods

Data collection of measured campsites consisted of the following: in March and May 1991, 125 campsites were measured--(89% of those in critical reaches, and 24% of those in non-critical reaches). Maps were drawn of all measured sites from laser xerox copies of June 1990 photographs, and areas suitable for camping were measured in m^2 at discharges of 142 m3/s, 226 m3/s, 425 m3/s, and 708 m3/s. Water's edge boundaries for 142, 226, and 425 m3/s were determined by aerial photographs and videos taken in 1990 and 1991. The water's edge boundary for 708 m3/s was delineated in the field by an experienced boatman by observing vegetation lines and cutbanks. Measured areas of campsites showed trends in the effects of river discharge on available campsite area and provided baseline information for monitoring studies.

Table 5. List of the 93 Campsites Evaluated

River Mile	River Side	Name	River Mile	River Side	Name
8.0	L/R	Jackass/Badger	119.2	R	No name
11.0	R	Soap Creek	119.8	L	120-mile
12.2	L	Below Salt Water Wash	120.0	R	Upper Blacktail
17.0	R	Lower House Rock	122.2	R	122-mile
18.0	L	Upper 18-mile	122.7	L	Upper Forster
19.0	R	Upper 19-mile	125.4	L	Below Fossil
19.1	L	Lower 19-mile	126.2	R	Randy's Rock
19.9	L	20-mile	131.1	R	Below Bedrock
20.4	R	Upper North Canyon	131.8	R	Galloway
21.5	L	22-mile Wash	132.0	R	Stone Creek
21.9	R	22-mile	133.0	L	133-mile
23.0	L	23-mile	133.5	R	Racetrack
23.7	L	Lone Cedar	134.6	L	Owl Eyes
26.3	L	Above Tiger Wash	136.0	L	Junebug
30.4	R	Below 30-mile	136.2	L	Opposite Deer Creek
31.6	R	South Canyon	136.3	L	Below Deer Creek
33.6	L	Below Redwall	136.9	L	Football Field
37.7	L	Tatahatso	137.0	L	Backeddy
39.0	R	Redbud Alcove	137.9	L	Doris
44.2	L	Eminence	139.0	R	Fishtail
47.2	R	Lower Saddle	139.8	L	140-mile
53.0	R	Main Nankoweap	145.1	L	Above Olo
56.2	R	Kwagunt	145.6	L	Olo
59.8	R	60-mile Canyon	148.4	L	Lower Matkat
61.7	R	Below LCR Island	148.5	L	Below Matkat
66.8	L	Espejo	155.7	R	Last Chance
74.1	R	Upper Rattlesnake	157.7	R	First Chance
74.3	R	Lower Rattlesnake	158.5	R	Second Chance
75.6	L	Neville's	160.0	L	160-mile
75.8	R	Papago	160.7	R	161-mile
76.6	L	Hance	164.5	R	Tuckup
81.3	L	Grapevine	166.6	L	Lower National
84.0	R	Clear Creek	168.0	R	Fern Glen
84.4	L	Above Zoroaster	174.3	R	Upper Cove
91.1	R	Lower 91-mile	174.4	R	Lower Cove
92.3	L	92-mile	177.7	L	Vulcan's Anvil
94.3	R	94-Mile	184.5	L	No name
96.0	R	96-mile	188.0	R	Upper Whitmore
96.1	L	Schist	188.2	R	Lower Whitmore
98.0	R	Upper Crystal	202.0	R	202-mile
102.8	R	No name	211.7	R	Fall Canyon
103.8	R	Emerald	212.9	L	Pumpkin Springs
107.8	L	Ross Wheeler	219.8	R	Upper 220-mile
108.0	R	Parkins' Inscription	219.9	R	Middle 220-mile
114.3	R	Upper Garnet	220.0	R	Lower 220-mile
114.5	R	Lower Garnet	222.0	L	222-mile

Campsite area during different IF years was determined by the following methods: laser xerox copies of aerial photographs taken in October 1992, May 1993, and May 1994 at 226 m3/s were made for each campsite to be measured. While visiting each site, useable area below 1991's delineation of 708 m3/s was assessed and outlined on the laser copies in 1992, 1993, and 1994 to comparewith 1991's area. Complete campsite area was evaluated and compared to 1991's campsite area. Useable area includes any area that is relatively flat (less than 9 degree slope), non-cobbled, and non-vegetated. While some of these spaces may be "used" for purposes of sitting, playing, or other recreation, they are not considered useable space because they do not contribute to the overnight carrying capacity of the site. Campsite area which was no longer useable in 1994 due to vegetation growth and flash flood damage was delineated and measured.

These laser copies were then scanned into a map and image processing system computer (MIPS) to compute campable area below the 708 m3/s zone as well as total campable area. Each image was calibrated while visiting the site by measuring the distance between two fixed points visible in the laser xerox, usually two large trees or shrubs, then entering these distances into the computer. Campsite area that was delineated in the field was then measured. For areas that are not visible from the air, such as space under overhangs, beneath vegetation, or space that is too small to be discerned on the video images (i.e. small separated sleeping areas), measurements were made in the field by taking the length and width of the area to the nearest half meter.

Ninety-three campsites were remeasured. Twenty-five of these sites were above the LCR, and 68 were below. Like in the 1991 study, emphasis was placed on campsites in critical reaches. Fifty-seven of the campsites were in critical reaches, and 36 were in non-critical reaches.The area of campsites during different interim flow years was determined by the following methods: Laser xerox copies of aerial photographs taken in October 1992, May 1993, and May 1994 at 8,000 cfs were made for each campsite to be measured. While visiting each site, useable area was assessed and outlined on the laser copies. Useable area includes any area that is relatively flat (less than 9 degree slope), non-cobbled, and non-vegetated. While some of these spaces may be "used" for purposes of sitting, playing, or other recreation, they are not considered useable space because they do not contribute to the overnight carrying capacity of the site.

Results

Changes in Campsite Area Between Years

Between spring 1991 and 1994, all measured campsites lost an average of 16% of their original area. Campsites above the LCR lost an average of 25%, while those below the LCR lost 13%. On average, critical reaches lost twice the percentage of original area (20%) as non-critical reaches (10%). These changes in area occurred primarily below 708 m3/s. Area changes below 708 m3/s accounted for the changed area for 74% of the sites between 1991 and 1994.

Changes in campsite area below 708 m3/s were evaluated annually (Table 6). Between spring 1991 and October 1992, three times as many campsites decreased as increased in size, resulting in a mean loss of 109 m^2. Campsites above the LCR lost more area than below the LCR (Figure 8, Table 6).

Between Oct 1992 and May 1993, this trend was reversed because of the January and February 1993 flooding events. Twice as many sites increased as decreased in size, resulting in a mean increase of 96 m^2. Increased size predominated below the LCR with a mean increase of 133 m^2, as expected since most of the sediment during the flooding events entered at the LCR. However, the mean loss in area of sites above the LCR was sharply reduced. Sites which gained the greatest area were not far downstream from the LCR. The first campsite downstream from the LCR (RM 61.7R) gained the most area, 1774 m^2, tripling the campsite's area below 708 m3/s. Even near the LCR, however, these changes were variable. Two campsites approximately 15 km downstream from the LCR (RM 74.1 and 74.3R) gained little to no area below 708 m3/s in 1993, while sites 2 km further downstream gained large areas. A number of campsites far downstream from the LCR also increased substantially in area. Most notable are RM 94.3R, which had lost its status as a camp in 1992 resulting from a drainage flash flood scouring out all campable area below 708 m3/s. By 1993 it could once more be used as a campsite, with more campable area below 708 than when first measured in 1991 and regained campsite status. RM 108.0R, 125.4L, 155.7R, and 220.0R also acquired considerable campsite area in 1993, with a mean increase of 496 m^2.

Between May 1993 and May 1994, the percentage of sites which increased versus decreased in size was very similar to that between 1991 and 1992, but the mean loss of campsite area was less than it was in 1992 at 64 m^2. In contrast to 1992, loss in campsite area predominated below the LCR, with a mean loss of 92 m^2. Antecedent conditions likely account for this loss in area, with the newly aggraded 1993 sand being unstable and more likely to erode. 73% of the campsites that increased in area below 708 m3/s in 1993 decreased in area by 1994, while only 28% of those that decreased or remained the same size in 1993 decreased in 1994.

TABLE 6. Changes in Campsite Area below 708 m3/s

	DECREASE	INCREASE	SAME	MEAN CHANGE, m^2	ABOVE LCR	BELOW LCR
SPR 91-OCT 92 n = 87	57%	22%	21%	- 109	- 153	- 93
OCT 92-MAY 93 n = 87	29%	55%	16%	+ 96	- 7	+ 133
MAY 93-MAY 94 n = 90	54%	28%	18%	- 64	+ 12	- 92
SPR 91-MAY 94 n = 86	49%	38%	13%	- 78	- 148	- 52

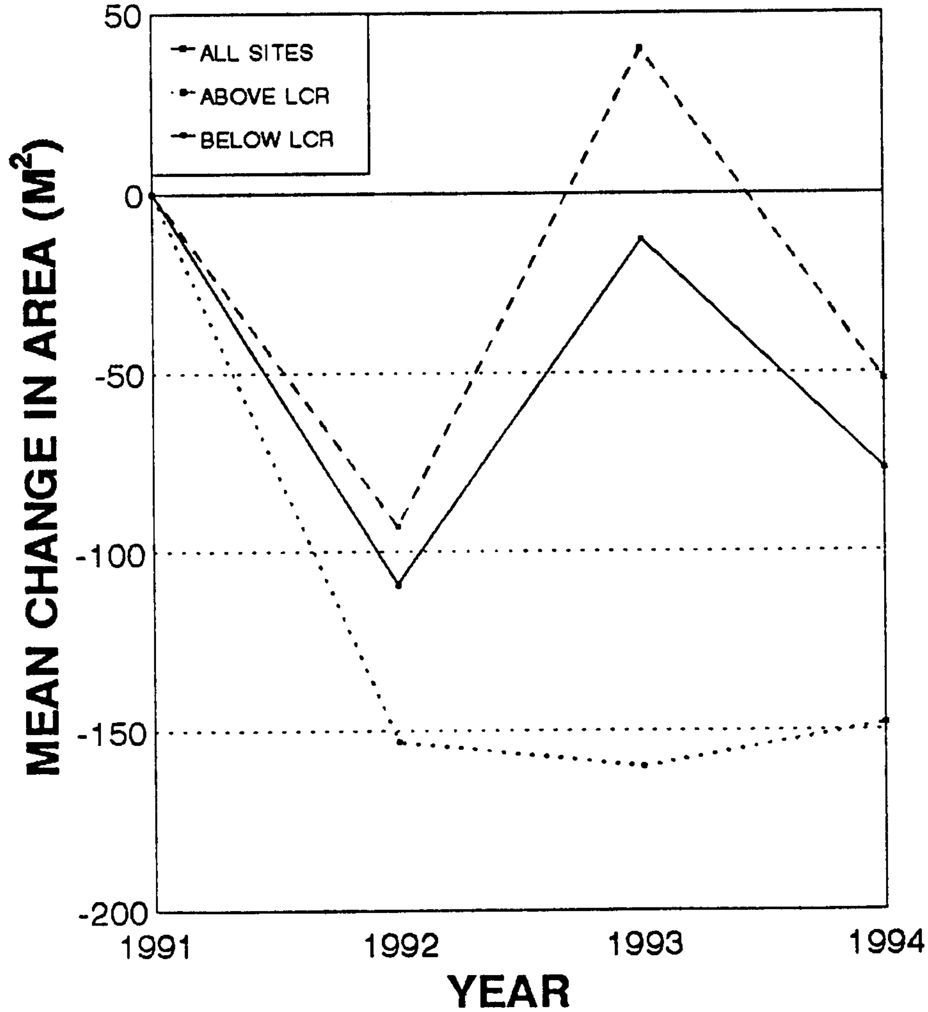


Figure 8. The mean change in campsite area between years for all sites in study, sites above the LCR, and sites below the LCR.

Factors Causing Decreased Campsite Area

Three factors causing a decrease in campsite area were discerned during campsite evaluation: 1) vegetation growth, 2) flash flooding, and 3) river-induced erosion or increases in the slope of sand.

Twenty-seven percent of the lost campsite area between 1991 and 1994 was caused by vegetation growth (Figure 9). Most (61%) of this vegetation growth occurred below 708 m3/s. A much higher percentage of the area lost below the LCR was due to vegetation growth (36%) than above the LCR (11%). The differences in vegetation growth between critical and non-critical reaches are even more pronounced. Nearly half (44%) of the loss in campsite area in non-critical reaches between 1991 and 1994 was caused by vegetation growth, compared with only 8% in critical reaches.

Flash flooding was responsible for 20% of the lost campsite area between 1991 and 1994 (Figure 9). This high percentage results from severe flash flooding that drastically affected campsites between RM 155 and 161. Heavy rains on August 20, 1993 caused debris flows which according to historical photographs had not occurred in that area for over 100 years. These debris flows destroyed two campsites, RM 157.7R and 160.9R, and flooding from this event severely limited the size of two campsites, RM 155.7R, and 158.5R. Unfortunately, these campsites are in close proximity to Havasu canyon, an area that has the largest discrepancy between campsite supply versus demand in the Grand Canyon. If this flooding event had not occurred, flash flooding would have been responsible for 6% rather than 20% of lost campsite area between 1991 and 1994. The percentage of lost area below the LCR due to flash flooding (26%) was three times higher than that above the LCR (9%, Figure 9). Flash flood damage occurred almost exclusively in critical reaches, causing 0% of the lost campsite area in non-critical reaches between 1991 and 1994 and 44% of that in critical reaches. These percentages, however, are also affected by the 1993 flooding event. If it had not occurred, 4% rather than 26% of lost area below the LCR would have been lost due to flash flooding, and 35% rather than 44% of the lost area in critical reaches would have been lost due to flash flooding between 1991 and 1994. Flash flooding caused the loss of an additional 936 m^2 in campsite area between 1991 and 1994, but both aggradation during the 1993 flooding events and flattening out of flash flood gullies enabled this additional area to be useable for camping by 1994.

Approximately half (53%) of campsite area lost between 1991 and 1994 was due to erosion of sand above 226 m3/s or to increased slope so that the sand could not be used for camping (Figure 9). The percentage of area lost due to these factors above the LCR (80%) was twice that as below the LCR (38%). Percentages in critical versus non-critical reaches were similar.

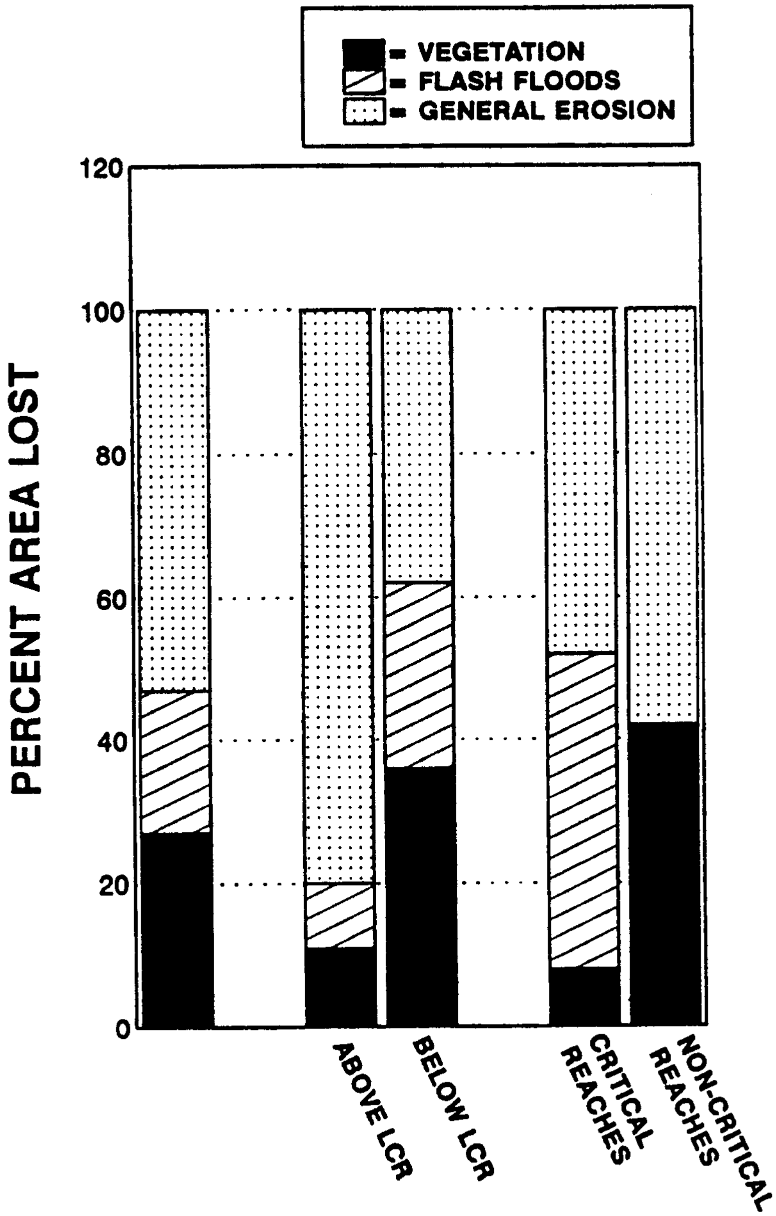


Figure 9. Percent camping area lost by vegetation growth, flash flooding, and general erosion causing sand loss above 226 m3/s or slope steepening. Percent campsite area lost above versus below the LCR caused by these factors. Percent area in critical versus non-critical reaches caused by these factors.

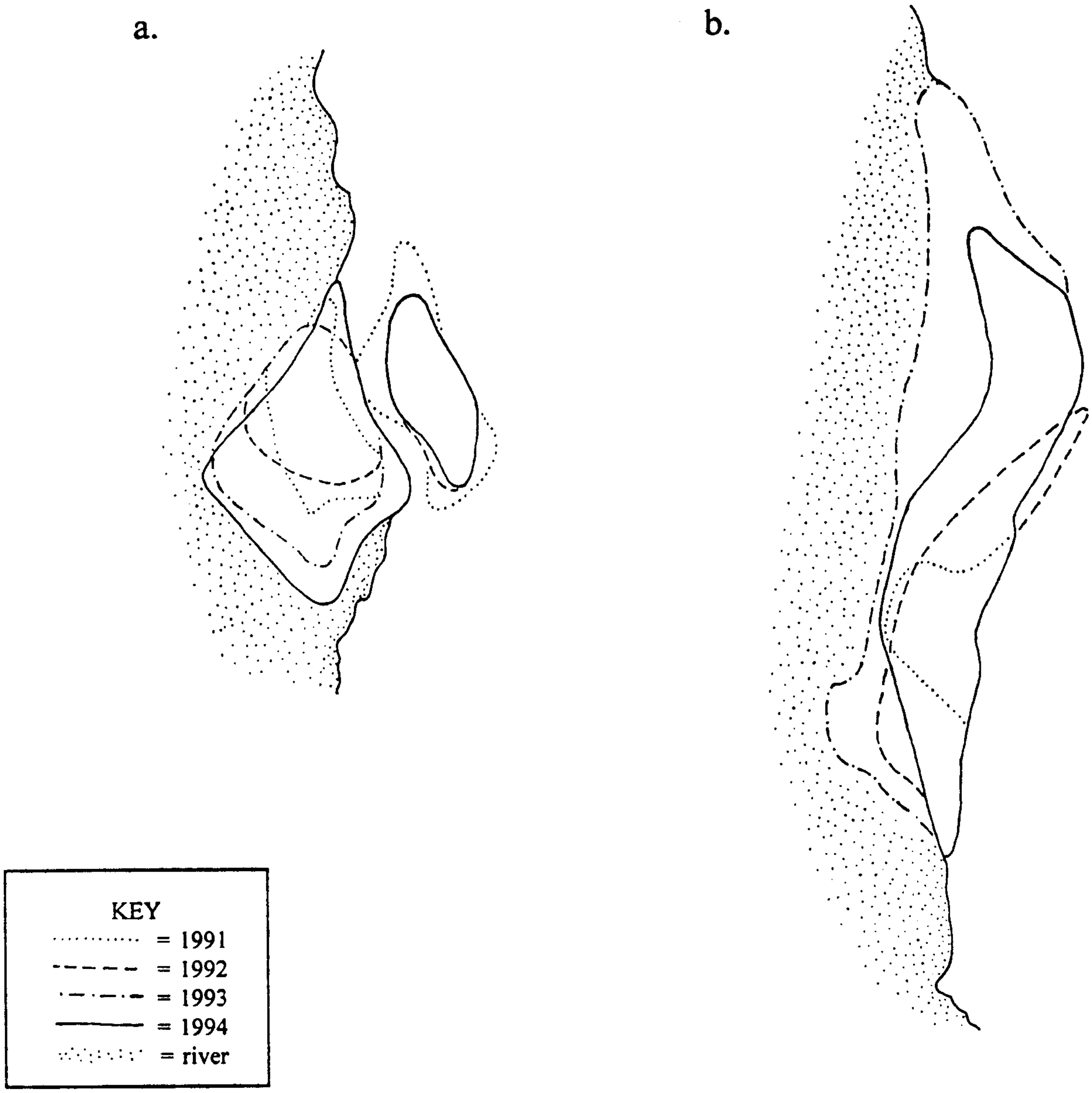


Figure 10. a) Campsite at RM 21.9R showing changes in campsite area below 708 m3/s between years. Low water area increased with each year, and higher terraced area decreased as river's edge of terrace migrated shoreward. b) Campsite at RM 61.7R, just downstream from the LCR, showing effects of 1993 flooding events on campsite area below 708 m3/s, with a large increase in 1993 and a substantial decrease in 1994.

DISCUSSION

Sand Bar and Recirculation Zone Adjustment to Interim Flows

Biannual surveys of sand bars along the Colorado River in Grand Canyon indicate that both the amount of sediment within the HAZ and the area available for camping was continuing to decrease as a result of IF operations from GCD. Nearly three years of interim flows from GCD have resulted in subaerial sand bar erosion, deposition at lower bar elevations, and increased sediment storage in recirculation zones as well as the main channel proximal to the sand bar (Figure 11A). Sediment is being eroded from high-elevation sand bar locations and deposition is occurring in a smaller recirculation zone along the lower portion of the sand bars below the maximum elevation of interim flows (Figure 11A). The downstream portions of reattachment bars are now exposed to main-current erosion due to contraction of the recirculation zones during the low discharge months of interim flow operations. Within the recirculation zones, the main platform of reattachment bars are being reduced in elevation. This increases the area that is inundated by IF and decreases the area available for recreational use.

IF operations from GCD have significantly affected the return current channel areas associated with reattachment bars. Return-current channels are an important component of the riparian ecosystem and provide critical habitat for endangered aquatic and riparian species (Turner and Karpiscak, 1980; Stevens and Waring, 1986; Valdez et al., 1992). Recirculation zones, and the reattachment bars/return channels associated with them, have decreased in size in response IF. Therefore, since implementation of IF, the number of suitable backwater habitats are decreasing (Bureau of Reclamation, 1994). If return channels are a desireable feature to GCNP resource managers, floods are needed to restructure return channels and increase the number of backwaters. Floods increase the number of backwaters by scouring the return-current channels and removing vegetation. Between flood events, backwaters decrease in size and number as they fill with sediment and become vegetated.

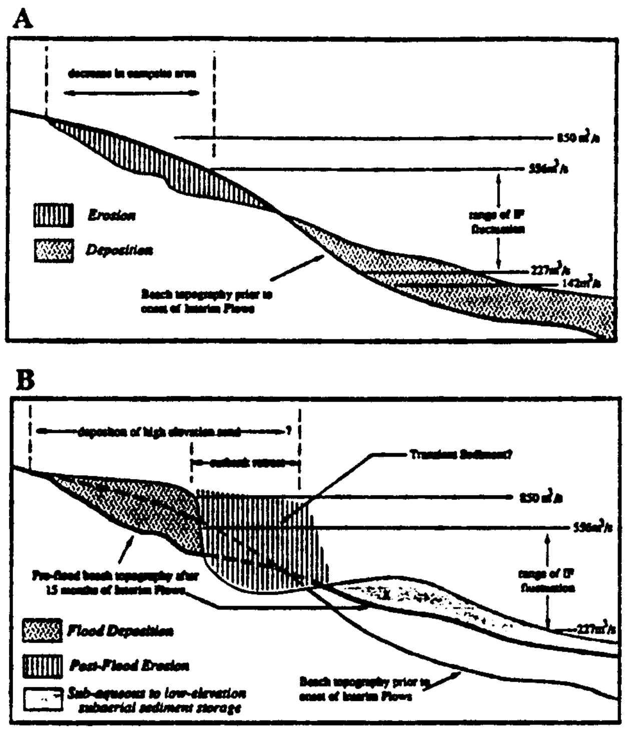


Figure 11. Schematic cartoon diagrams (not to scale) illustrating, A) erosional and depostional relationships during IF prior to the winter 1993 floods, and B) flood deposition, post-flood cutbank retreat, and low-elevation subaerial and subaqueous deposition.

Trends of Spatial Change in Campsite Area

While responses of individual campsites to interim flows varied widely, there was a trend of increased area just above 226 m3/s during one or more years at 52% of the sites. However, 35% of the sites exhibited an decrease in this low water area. Many of these changes occurred in response to the 1993 LCR flooding events with an increase in 1993 and a decrease in 1994 of low water area. Also, at 13 sites, terraces at approximately 708 m3/s became narrower as they calved off along the river's edge. Examples of these changes are pictured in Figure 10.

Since the initiation of IF, campsite area has decreased, particularly in critical reaches. Since changes in campsite area through time were not evaluated before IF, we cannot compare this decrease in area to pre-IF decreases. However, flash flood damage and vegetation growth above 708 m3/s occurs independently of IFs. This study does demonstrate the benefits of flooding under conditions similar the January and February 1993 events on campsite area. Those events benefitted campsites even more than this study indicates since campsite area rather than sand volume was measured. There were many instances where more sand was observed, creating higher sand terraces after the 1993 flooding events but where campsite area remained the same.

Other than measurements of areas below 708 m3/s, there is no relationship between discharge and campsite area in this study. Flat area just above 226 m3/s, while substantial at some campsites, would not be used for camping if the river level fluctuated. It would be and has been used during constant flows. However, if access is equal, campsite space near or within large vegetation (above 708 m3/s) is preferred for reasons of protection, aesthetics, and privacy.

Responses to a Tributary Floods

Downstream from the confluence of the LCR and Colorado River, the three 1993 winter flood events augmented the sediment budget and increased main stem transport rates. Sand bars aggraded considerably in size with deposition of up to 1-2 meters of sediment above current interim flow fluctuations (Figure 11B). Subaqueous aggradation within both the main channel and eddy systems was substantial. Up to four meters of aggradation occurrred along the channel floor and recirculation zones at 68 Mile (Appendix A; 68R). Burkham (1987) reported that bed elevation in the pool at the USGS gauging station near Phantom Ranch changed as much as 2.5 meters annually before the construction of GCD and subsequent flow regulation. Just upstream from this gauge at 87 Mile, cross-channel profiles show that up to 2 m of sand was still stored on the bed 9 months after the LCR flood events (Appendix A; 87L). Similiar aggradation was apparent as far downstream as RM 93 (Appendix A; 93L). Several sites farther downstream (Appendix A; 119R and on), however, show a decrease in sediment storage in recirculation zones and the main channel. These observations imply that sediment input from the LCR was transported and redistributed up to 30 miles downstream of the LCR-Colorado River confluence. Below this zone high-elevation sand bar aggradation resulted from redistribution of pre-existing sediment stored on the riverbed.

The newly aggraded sand bars quickly destabilized after the return to normal GCD interim flow operations and large-scale cutbanks, some up to 2.5 m high, were observed at virtually every study site downstream of the LCR-CR confluence. Erosion rates increased dramatically after the 1993 flood events, as was reported after the 1983 "spill" (Brian and Thomas, 1984; Beus et al., 1985; Schmidt and Graf, 1990). Two months after the 1993 flood events, the response of sand bars to interim flows was re-established (Figure 11B). This response is characterized by erosion of the higher elevation portions of sand bars, and aggradation along the lower portions of sand bars. Continued interim flow operations without flood flows can be expected to result in continued erosion of the upper portions of the sand bars, resulting in a loss of both camping area, and riparian/wildlife habitat.

Management Implications

We conclude that interim flow objectives are only partially being met. Sediment accumulated in recirculation zones and the main channel proximal to the sand bars, but erosion of sediment at higher bar elevations was not being replaced. Because of reduced capacity to transport sand, the Colorado River is now storing more sand in low velocity areas such as recirculation zones and upper pools above constrictions. This gain in sand storage, especially between the Paria and LCR, is potentially the principal sediment source for rebuilding sand bars.

Periodic high-flow releases from GCD are needed to redistribute sediment to higher sand bar elevations and restructure return current channels. The 1993 winter floods provided an unexpected test case of a bar-building flow event. Following these flood events, deposition of new and stored riverbed sediment was documented throughout the system downstream of the LCR. Our observations suggest that sediment accumulated along the bottom of the river was successfully reditributed to higher bar elevations. Based on existing data, a dam operating strategy that combines IF releases with flood flows from GCD is recommended. Continued monitoring and research is needed to determine the effects of this, and future dam management strategies.

CONCLUSIONS

Interim flow operations from GCD have led to erosion of the higher elevation portions of sand bars.

Interim flow operations from GCD have resulted in deposition below the maximum interim flow stage elevation along the lower portions of many sand bars, including the return current channnels of reattachment bars.

Occasional "bar-building flows" near, or in excess of GCD power-plant capacity are necessary to redistribute sediment from river-storage to bar elevations not reached by GCD interim flows.

"Bar-building flows" at or near powerplant capacity are feasible.

The antecedent condition of recirculation zones has an important influence on depositional patterns of sand bars; Eddies that are empty tend to gain sediment, eddies that are full do not.

The majority of the 62.4 Mile reattachment bar was deposited during the 72 hour duration of the first January flood.

A minimum of 64.644 m^3 of sediment was depsoited in the 62.4 Mile recirculation zone during the floods at deposition rates as high as 0.79 kg/s.

Changes in dam-release patterns following flood deposition at 62.4 Mile had a pronounced effect on erosion rates at the site. An order of magnitude change in erosion rates at the site was observed after dam operations changed to high volume interim flows on July 1, 1993. The longevity of newly re-formed sand bars is dependent on a dam operation strategy that attempts to limits bank erosion processes.

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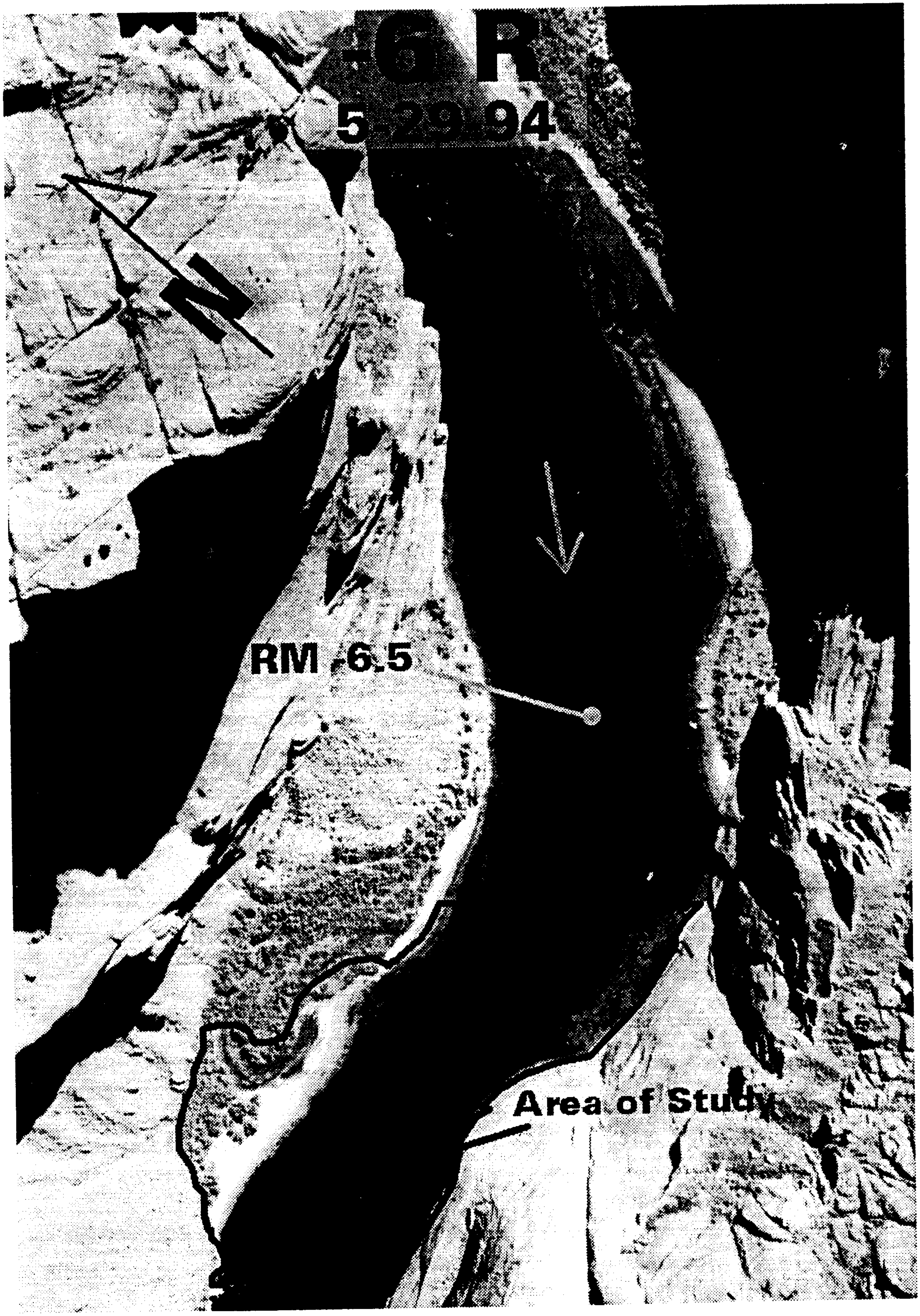
APPENDIX A

Atlas of Sandbar Survey Sites*

* Survey Sites 62R and 68R contain the format that will be produced for all sites in the final report



6 R
5 29 94
N
RM 6.5
Area of Study

GCES BEACH SURVEY

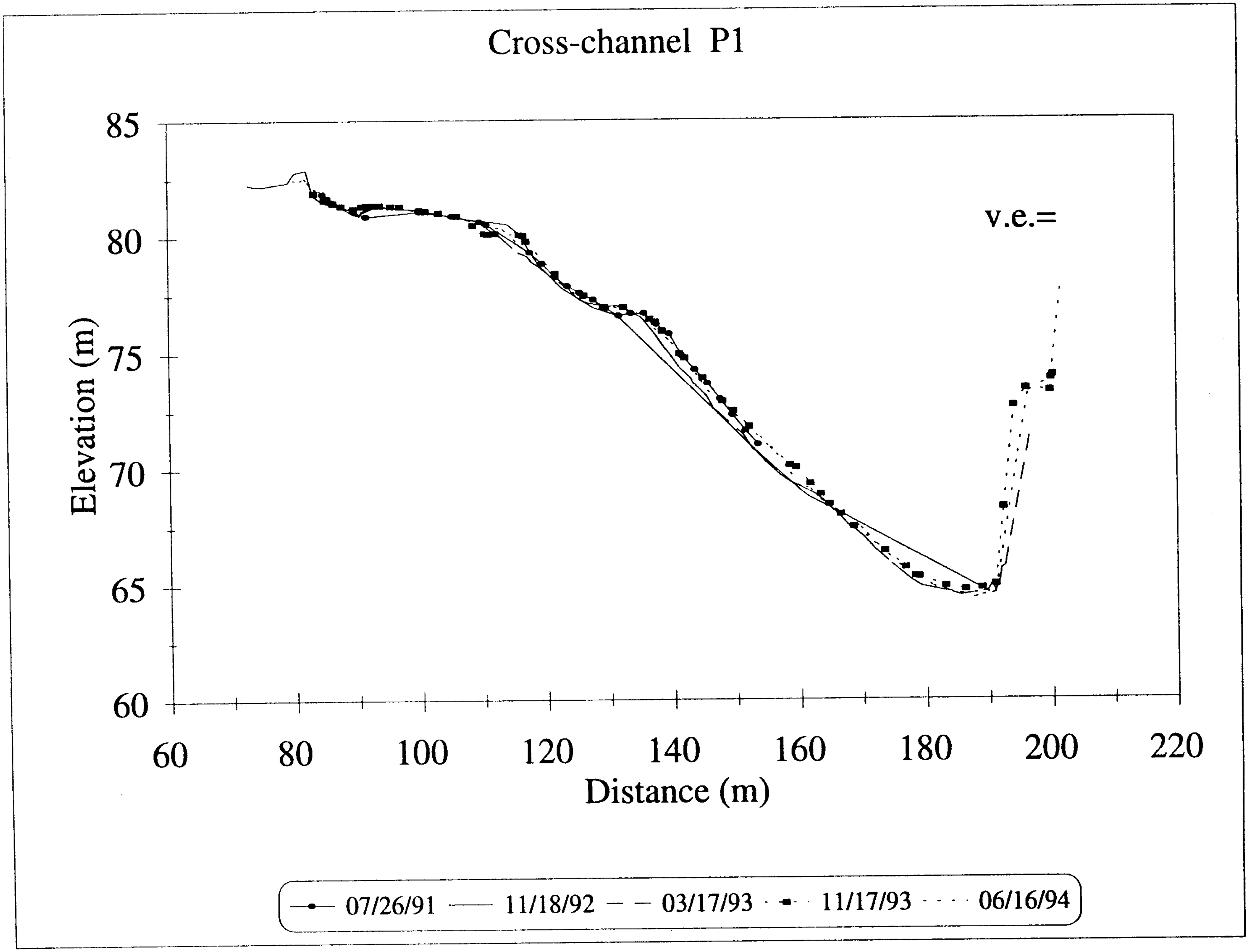
B02

GR-B02

6 MILE 11-17-93

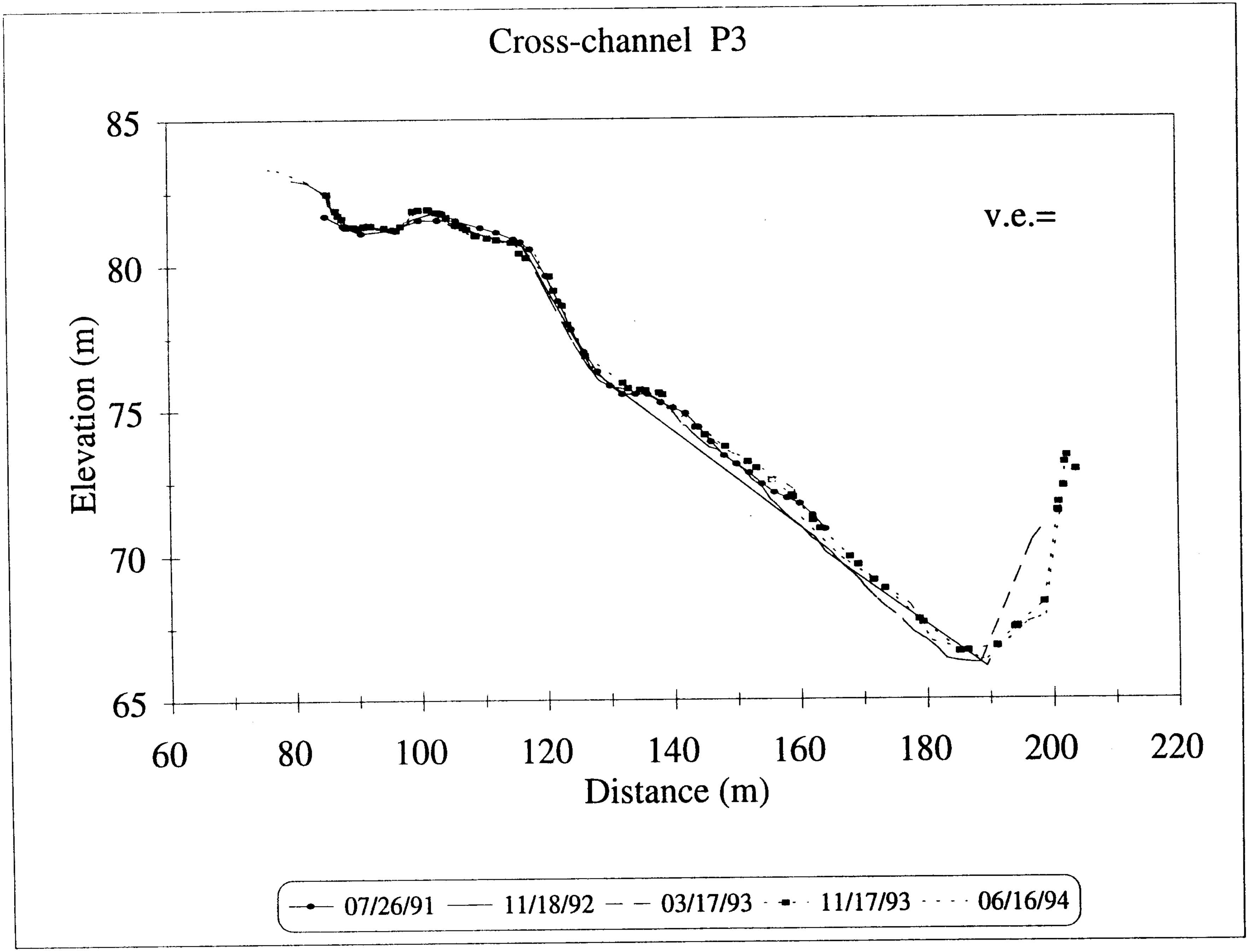
1: 750

-6 Mile



Cross-channel P1
85
80
75
70
65
60
Elevation (m)
60
80
100
120
140
160
180
200
220
Distance (m)
v.e.=
07/26/91
11/18/92
03/17/93
11/17/93
06/16/94

-6 Mile


Cross-channel P3
v.e.=
Elevation (m)
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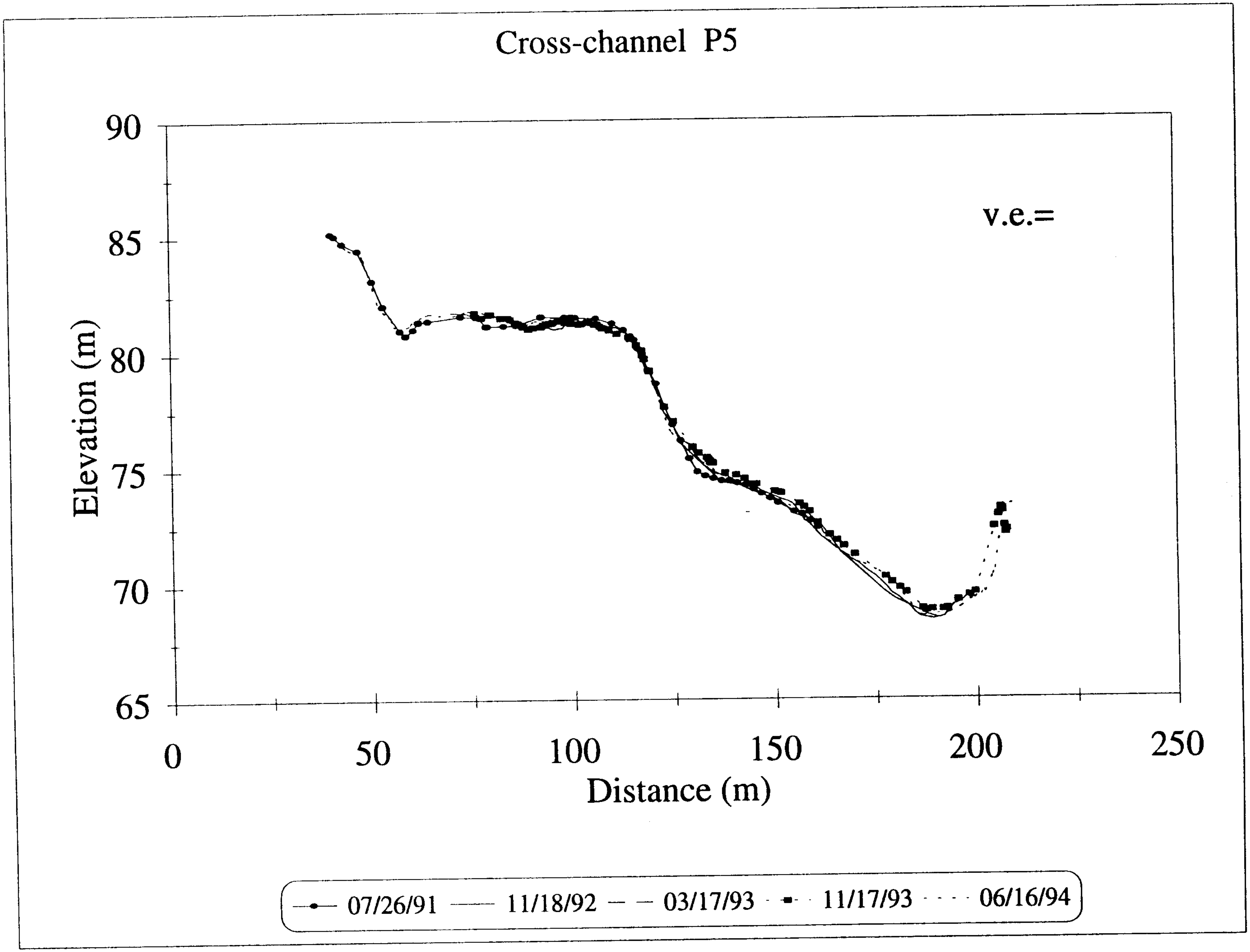
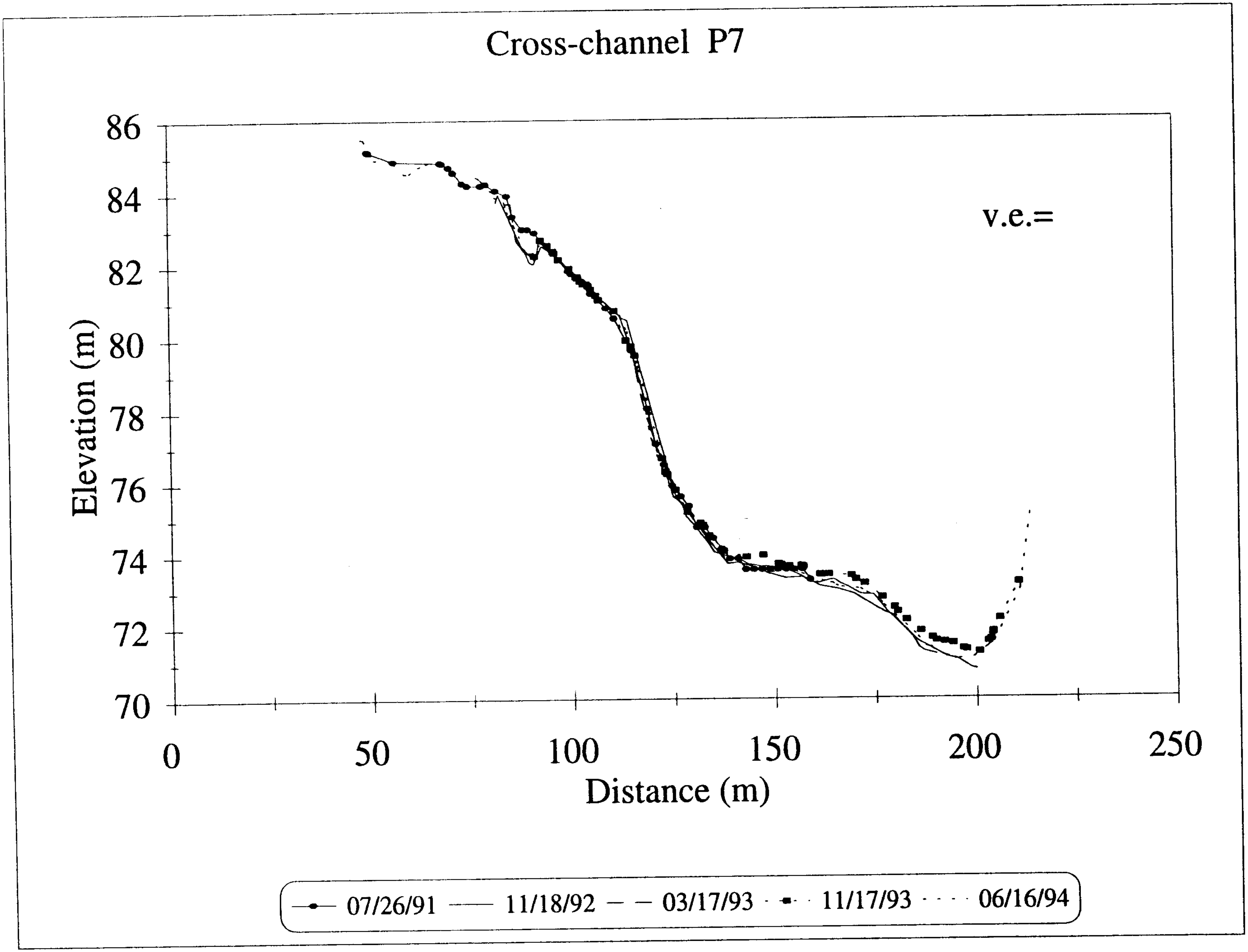
80
75
70
65
60
80
100
120
140
160
180
200
220
Distance (m)
07/26/91
11/18/92
03/17/93
11/17/93
06/16/94

-6 Mile



Cross-channel P5
v.e.=
90
85
80
75
70
65
Elevation (m)
0
50
100
150
200
250
Distance (m)
07/26/91
11/18/92
03/17/93
11/17/93
06/16/94

-6 Mile


Cross-channel P7
v.e.=
Elevation (m)
86
84
82
80
78
76
74
72
70
0
50
100
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Distance (m)
07/26/91
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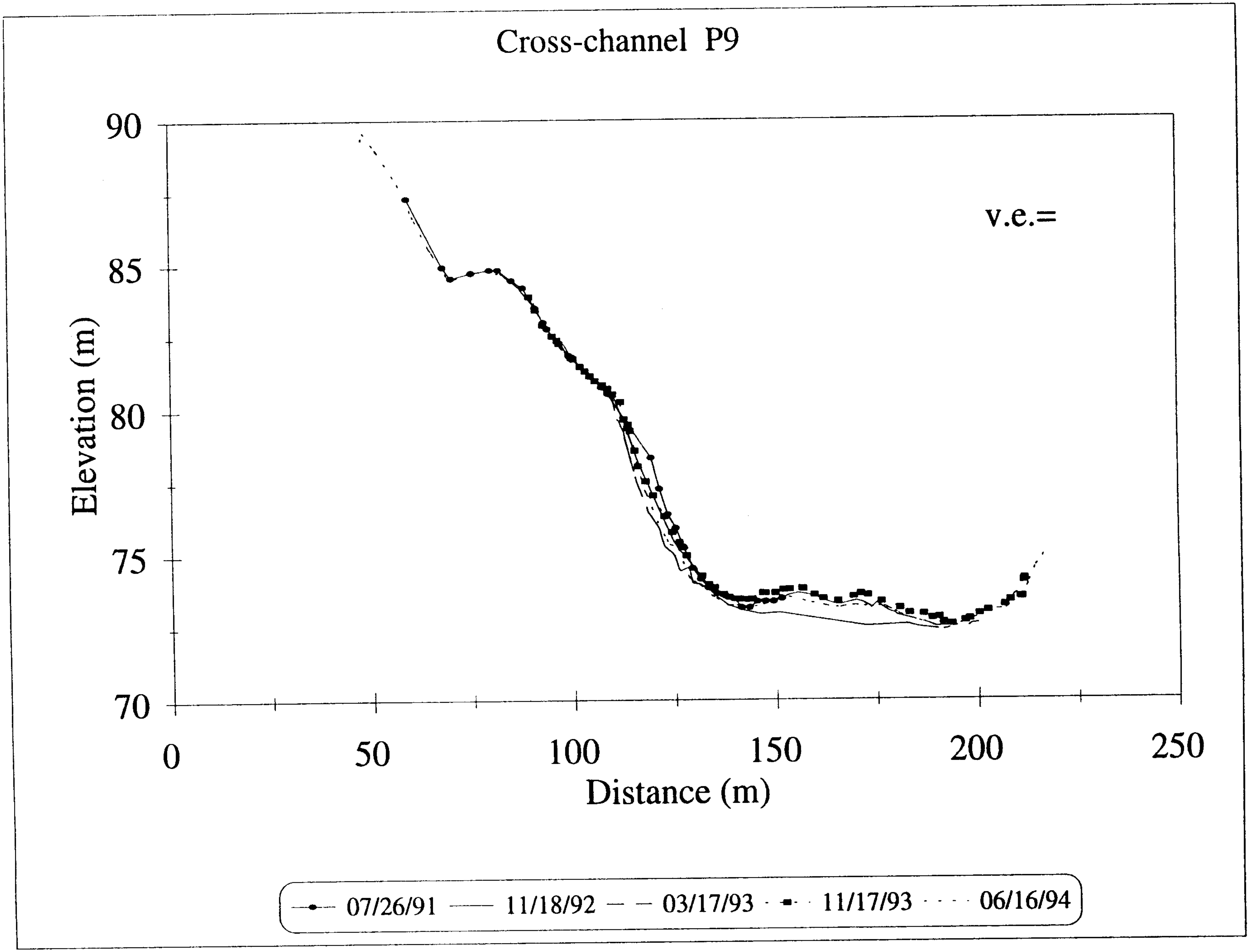
03/17/93
11/17/93
06/16/94

-6 Mile


Cross-channel P9
v.e.=
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85
80
75
70
Elevation (m)
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50
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200
250
Distance (m)
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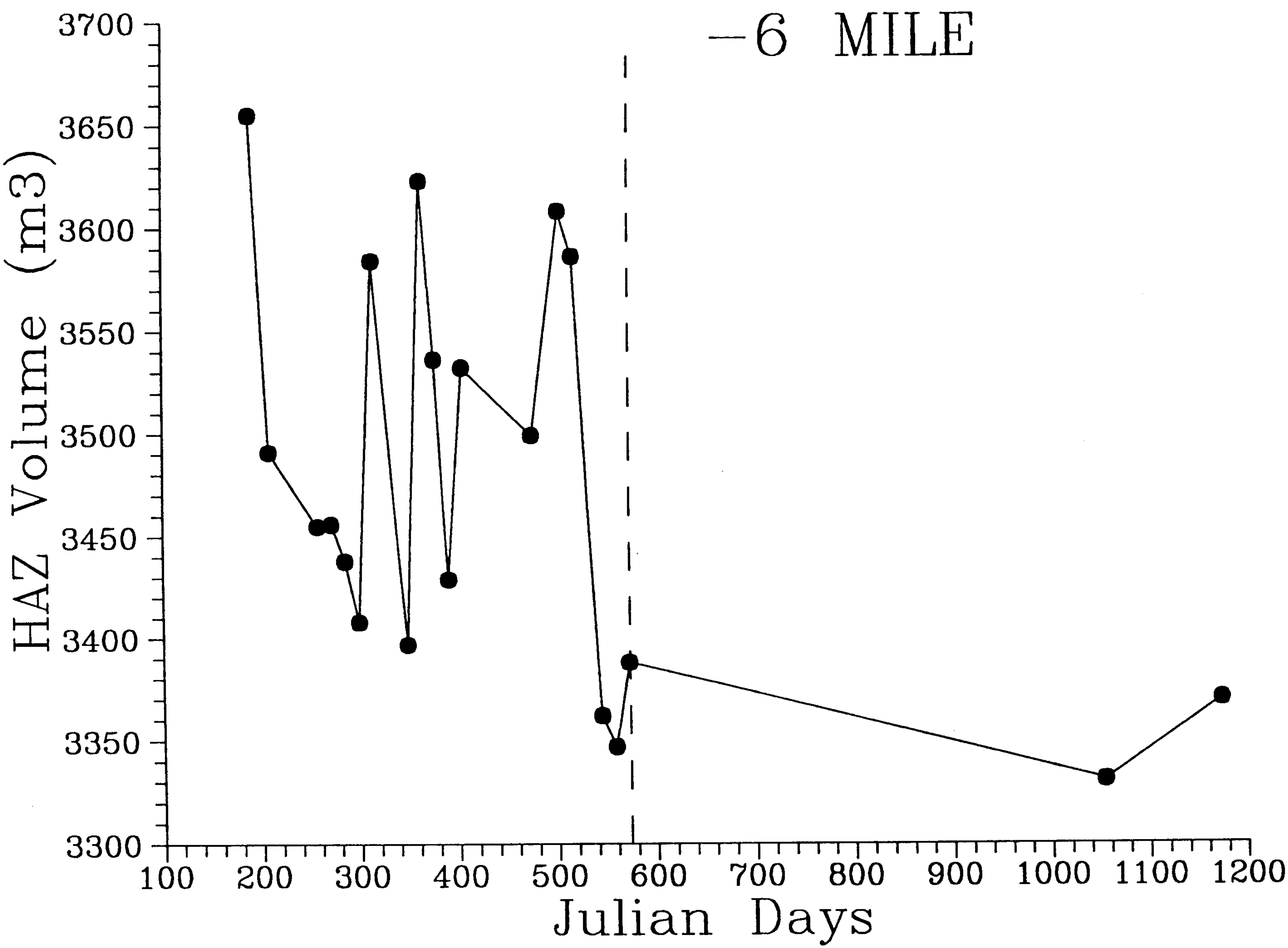
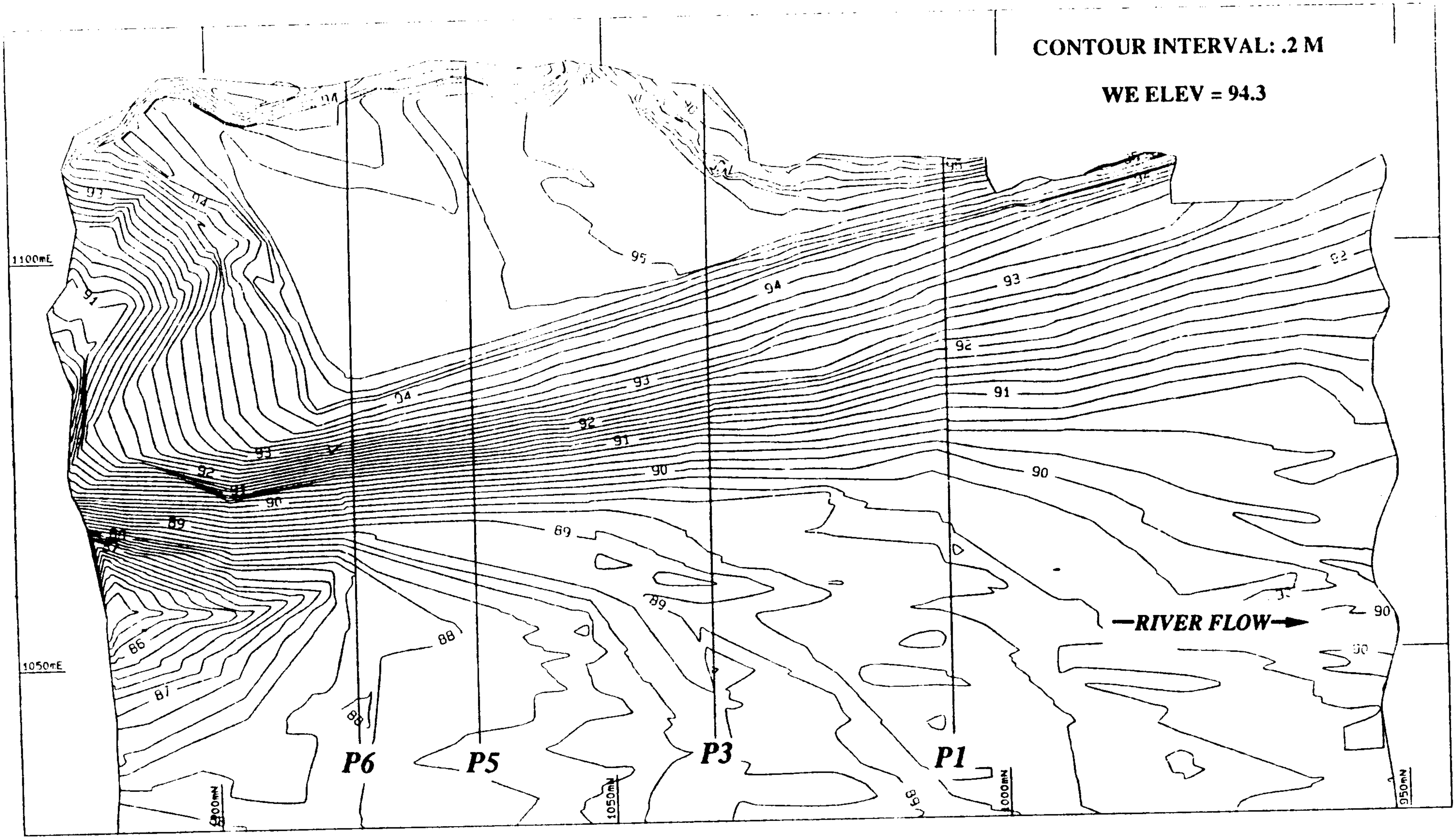
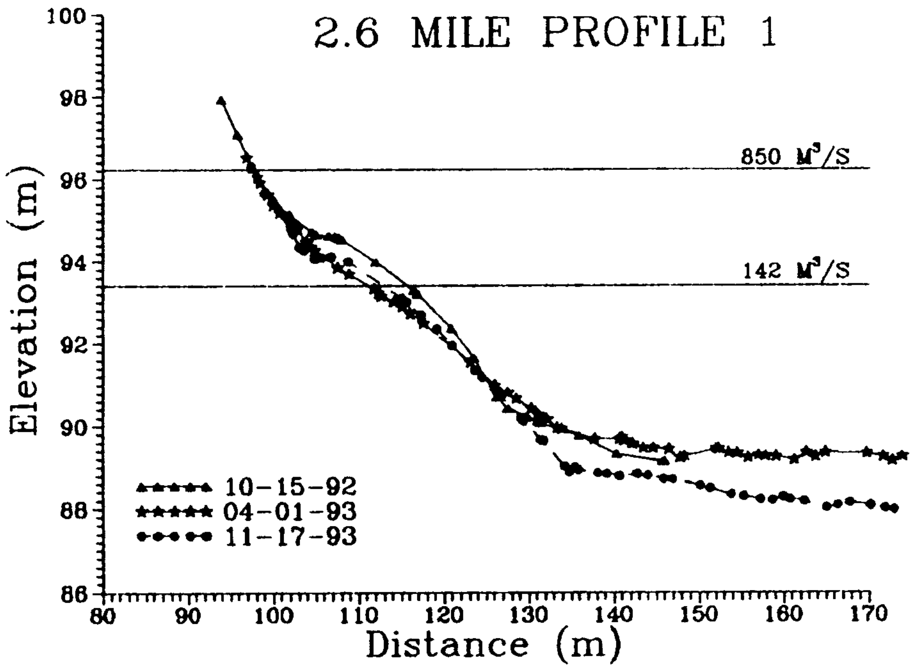
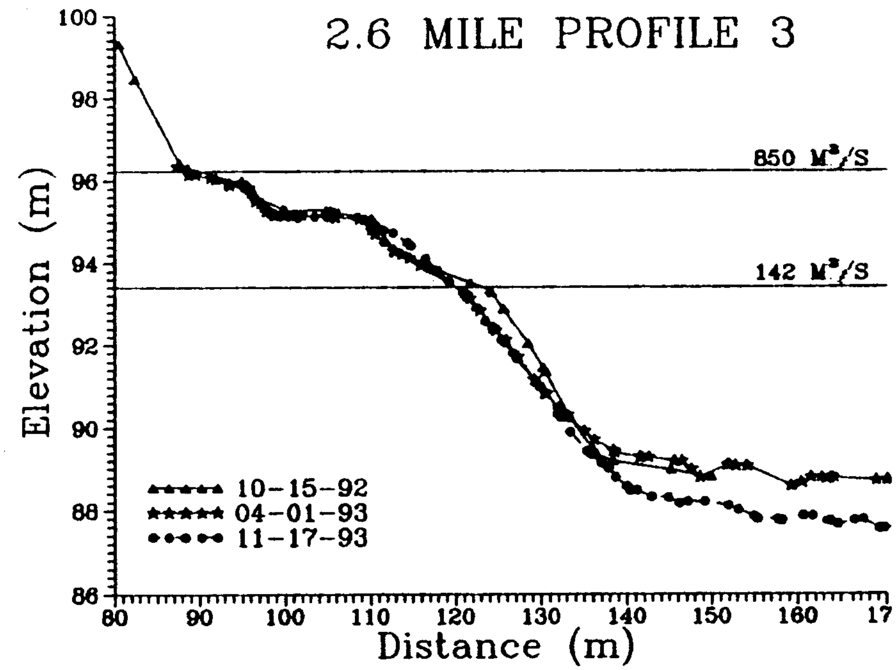
11/17/93
06/16/94

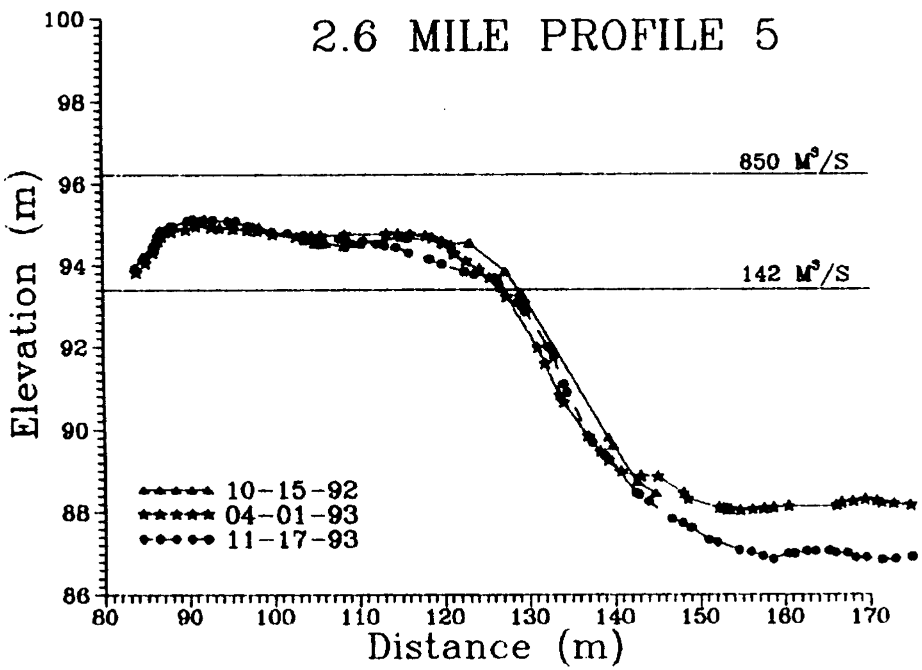

-6 MILE
HAZ Volume (m3)
3700
3650
3600
3550
3500
3450
3400
3350
3300
100
200
300
400
500
600
700
800
900
1000
1100
1200
Julian Days

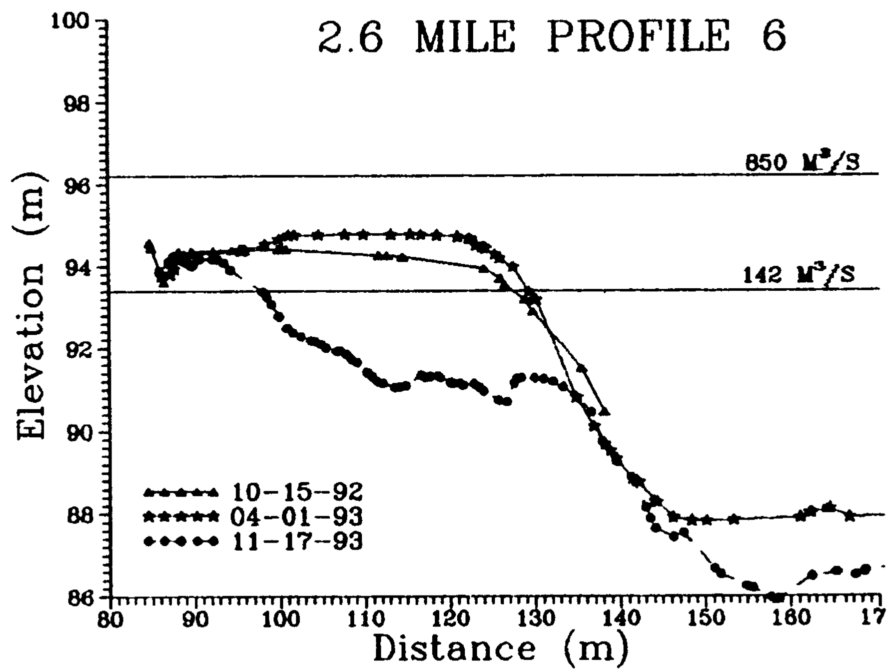

3 L
5-29-94
Area of Study
RM 2.5

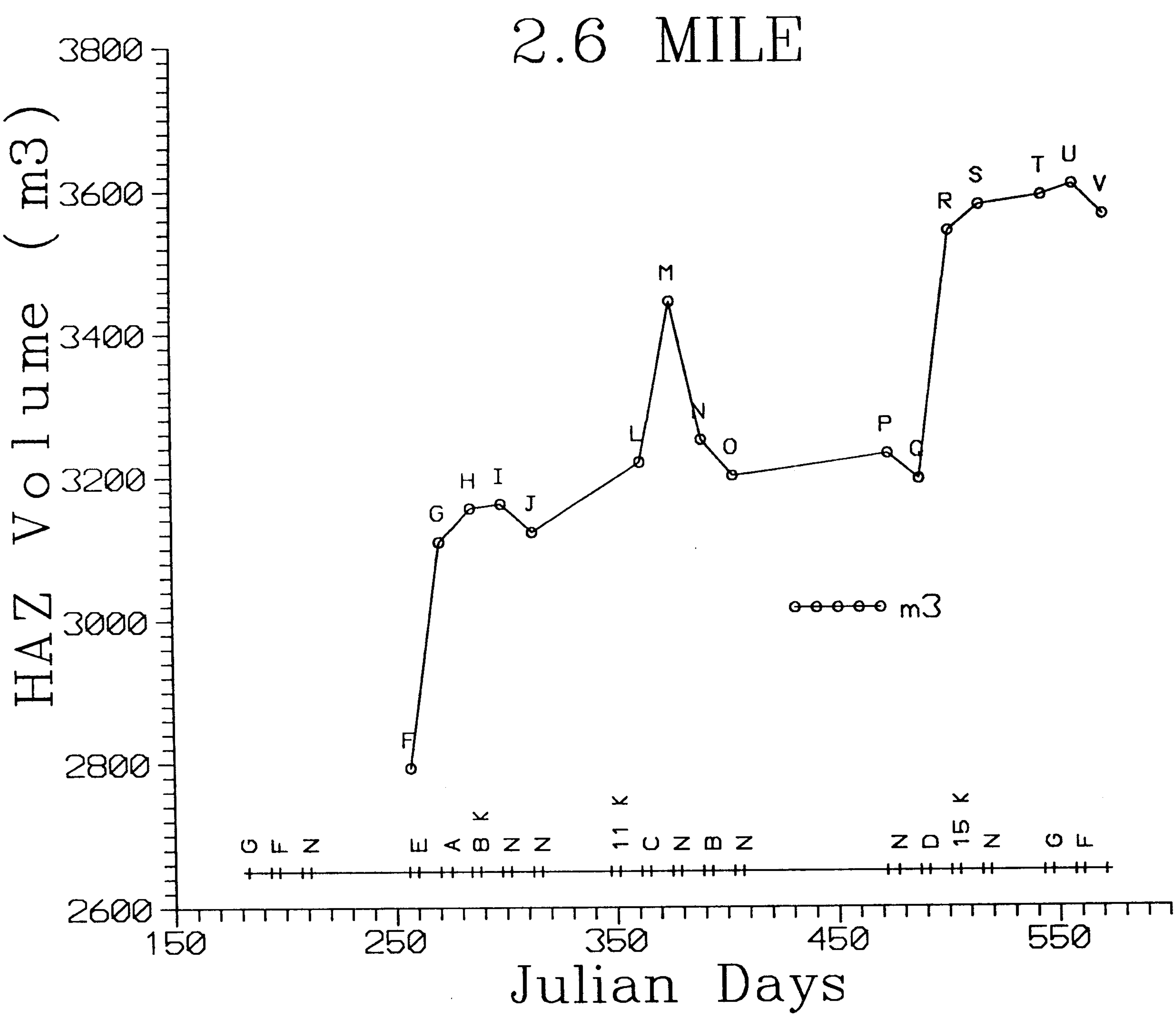

CONTOUR INTERVAL: .2 M
WE ELEV = 94.3
—RIVER FLOW→
P6
P5
P3
P1
1100mE
1050mE
1000mN
1050mN
950mN

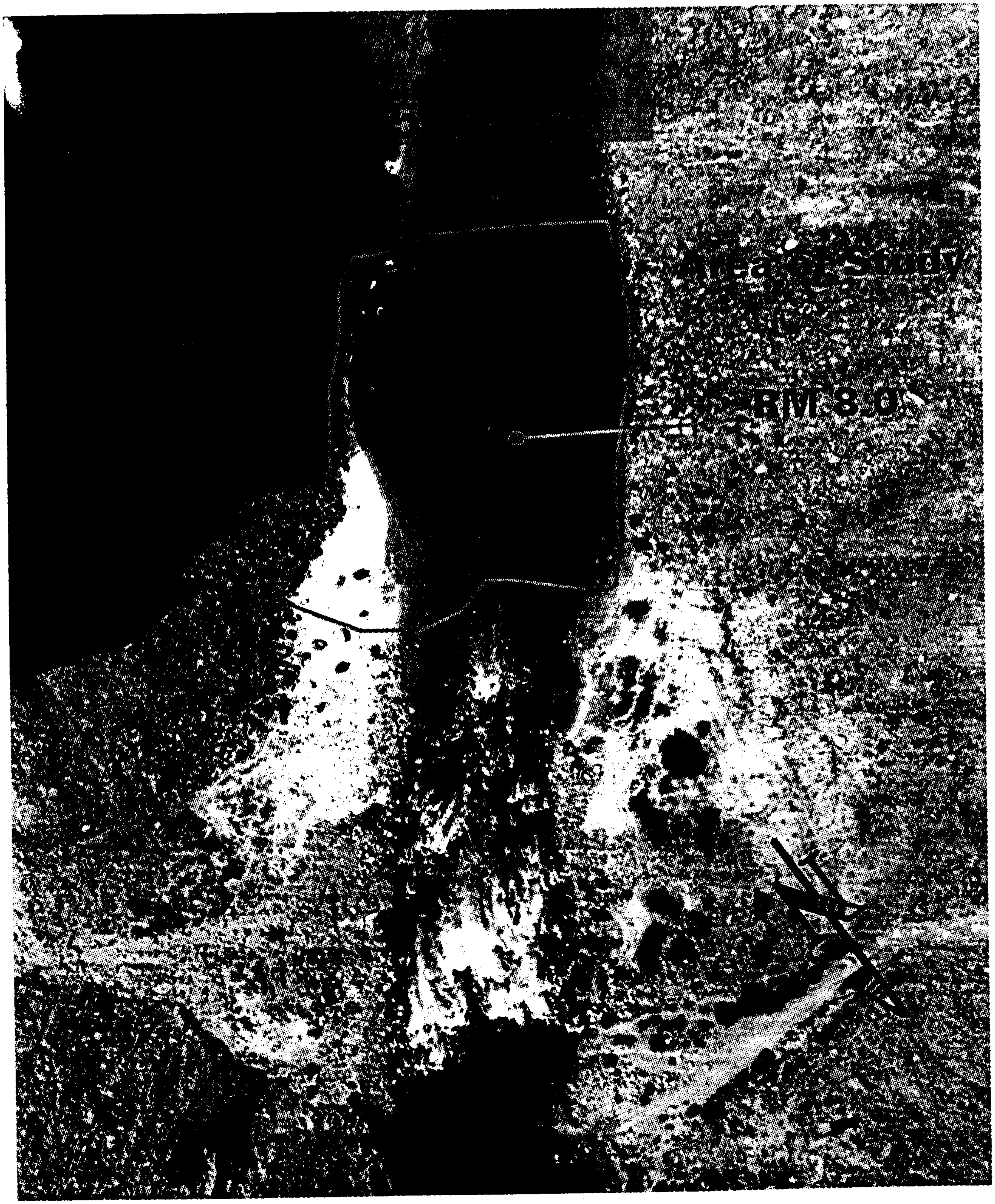

2.6 MILE PROFILE 1
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-15-92
04-01-93
11-17-93

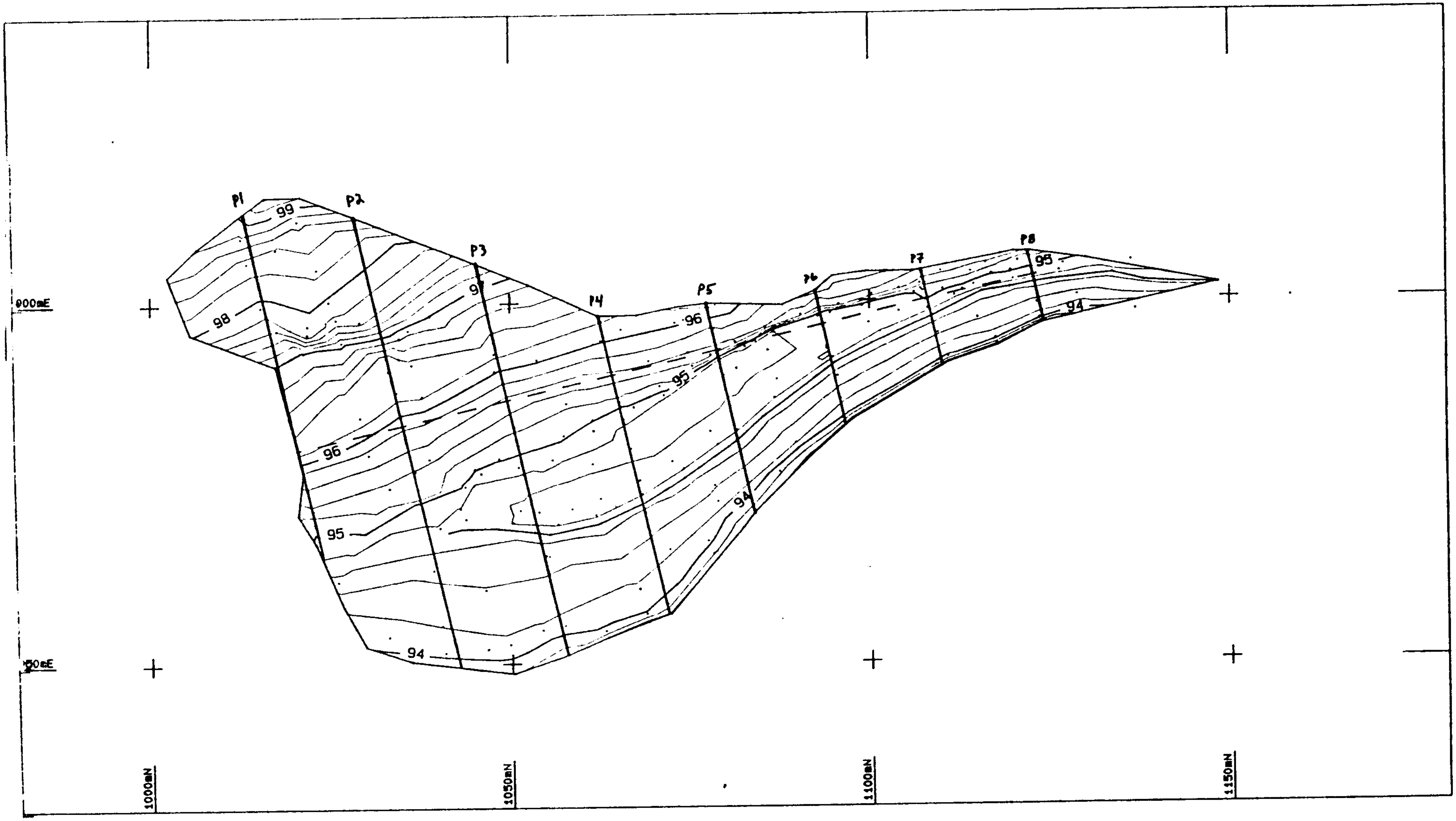

2.6 MILE PROFILE 3
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-15-92
04-01-93
11-17-93


2.6 MILE PROFILE 5
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-15-92
04-01-93
11-17-93

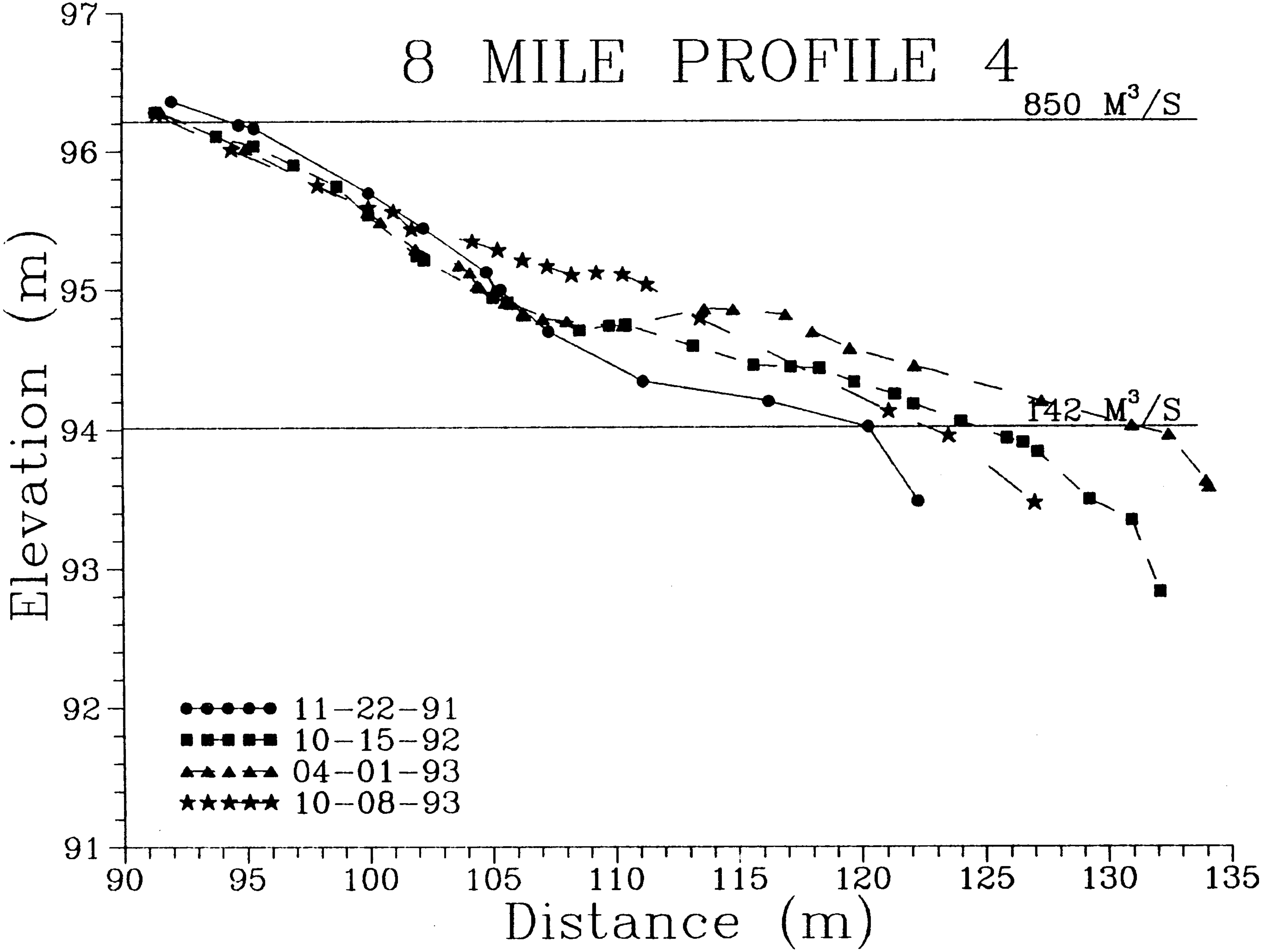

2.6 MILE PROFILE 6
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-15-92
04-01-93
11-17-93

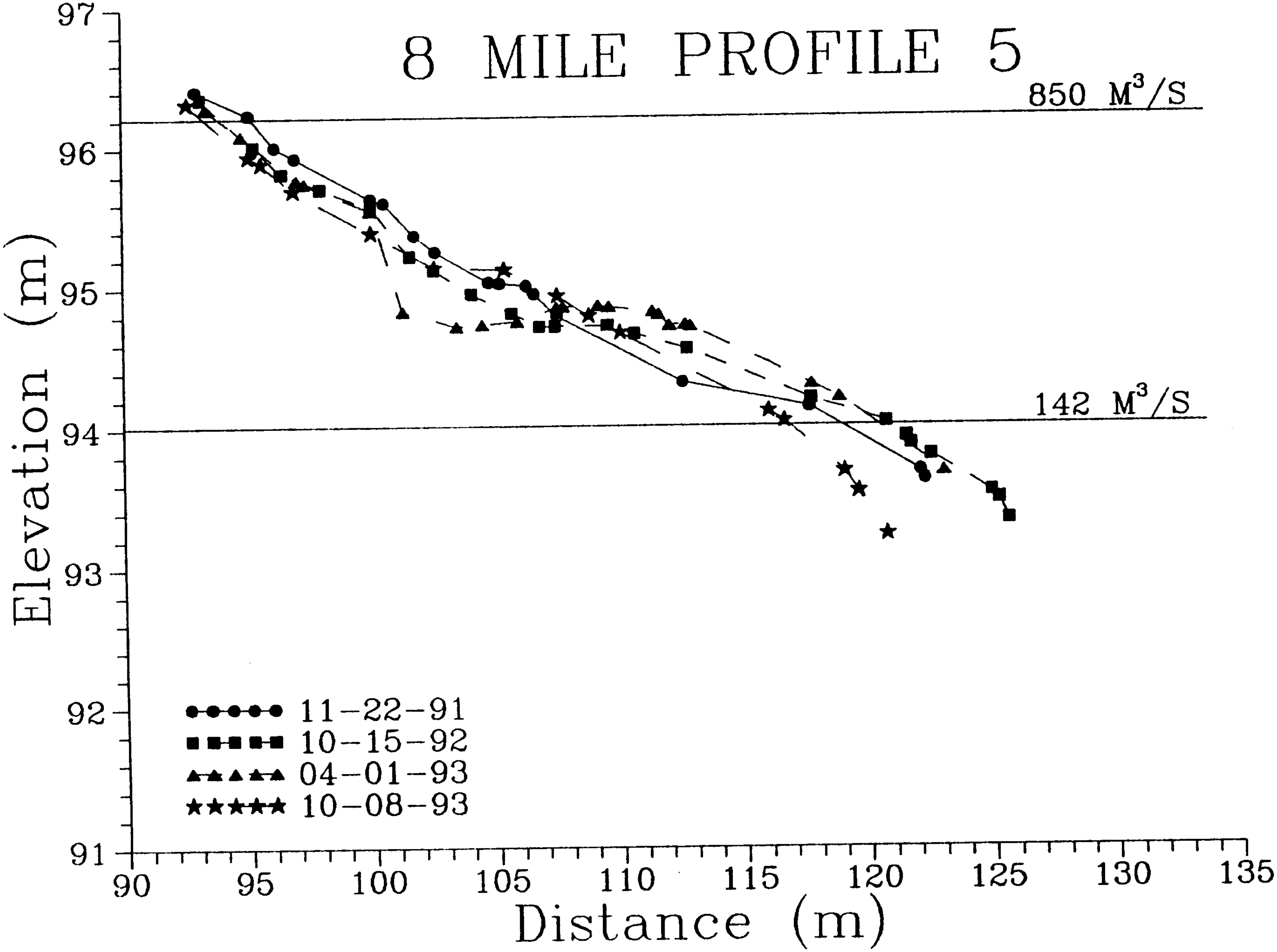

2.6 MILE
HAZ Volume (m3)
3800
3600
3400
3200
3000
2800
2600
150
250
350
450
550
Julian Days
m3


Area of Study
RM 8.0

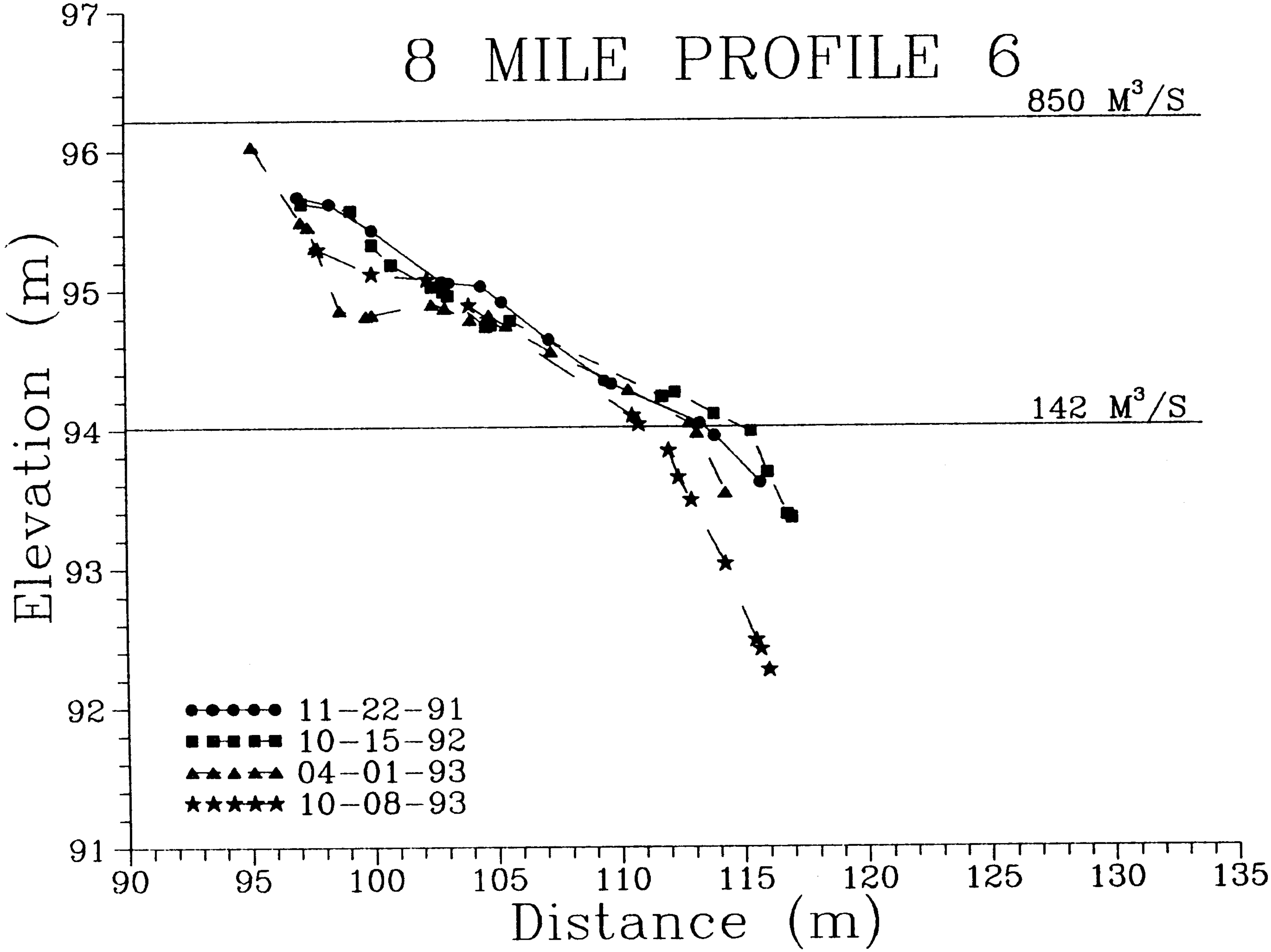


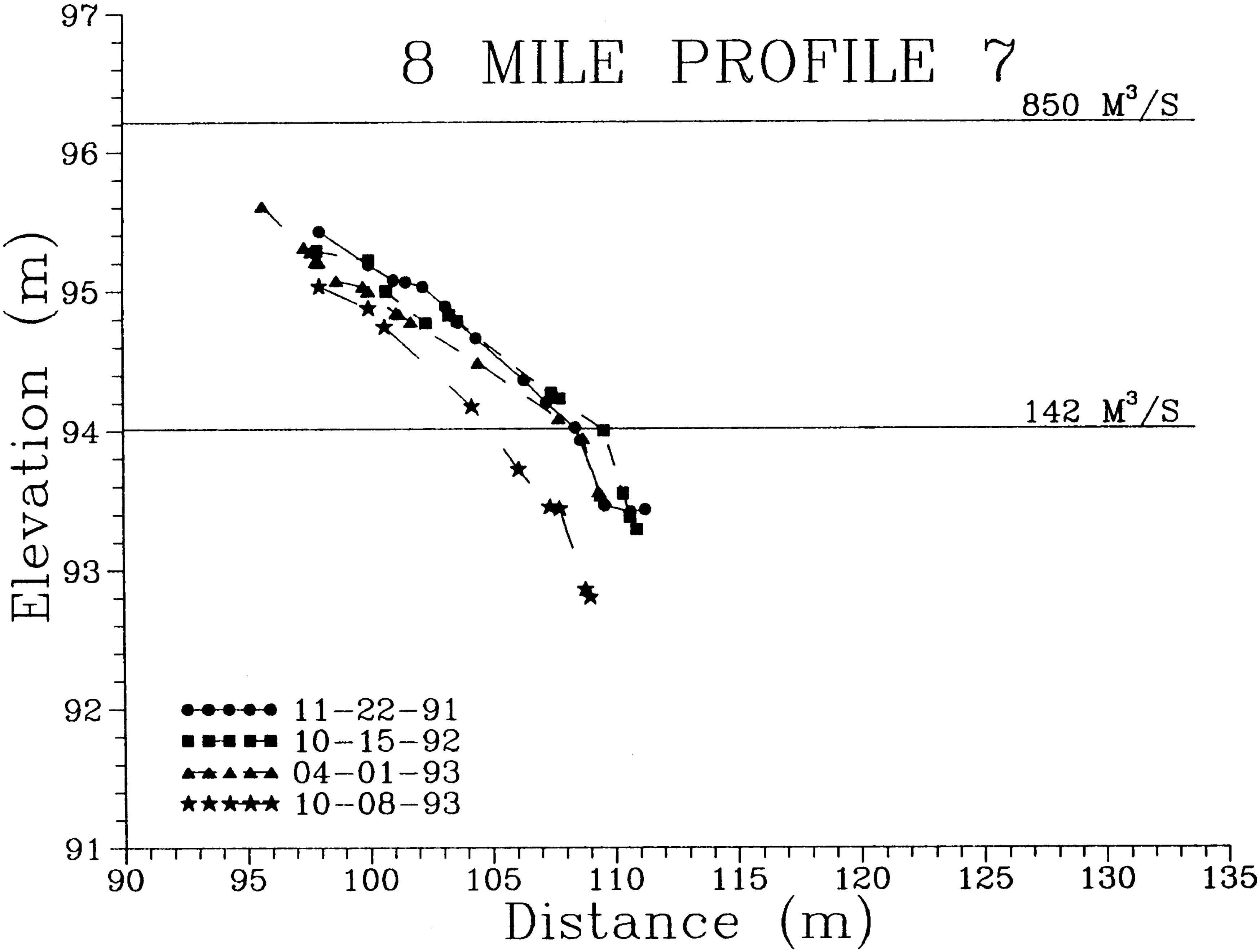
GCES BEACH SURVEY 04Z 08L-04Z 8 MILE 04-01-93 1: 500

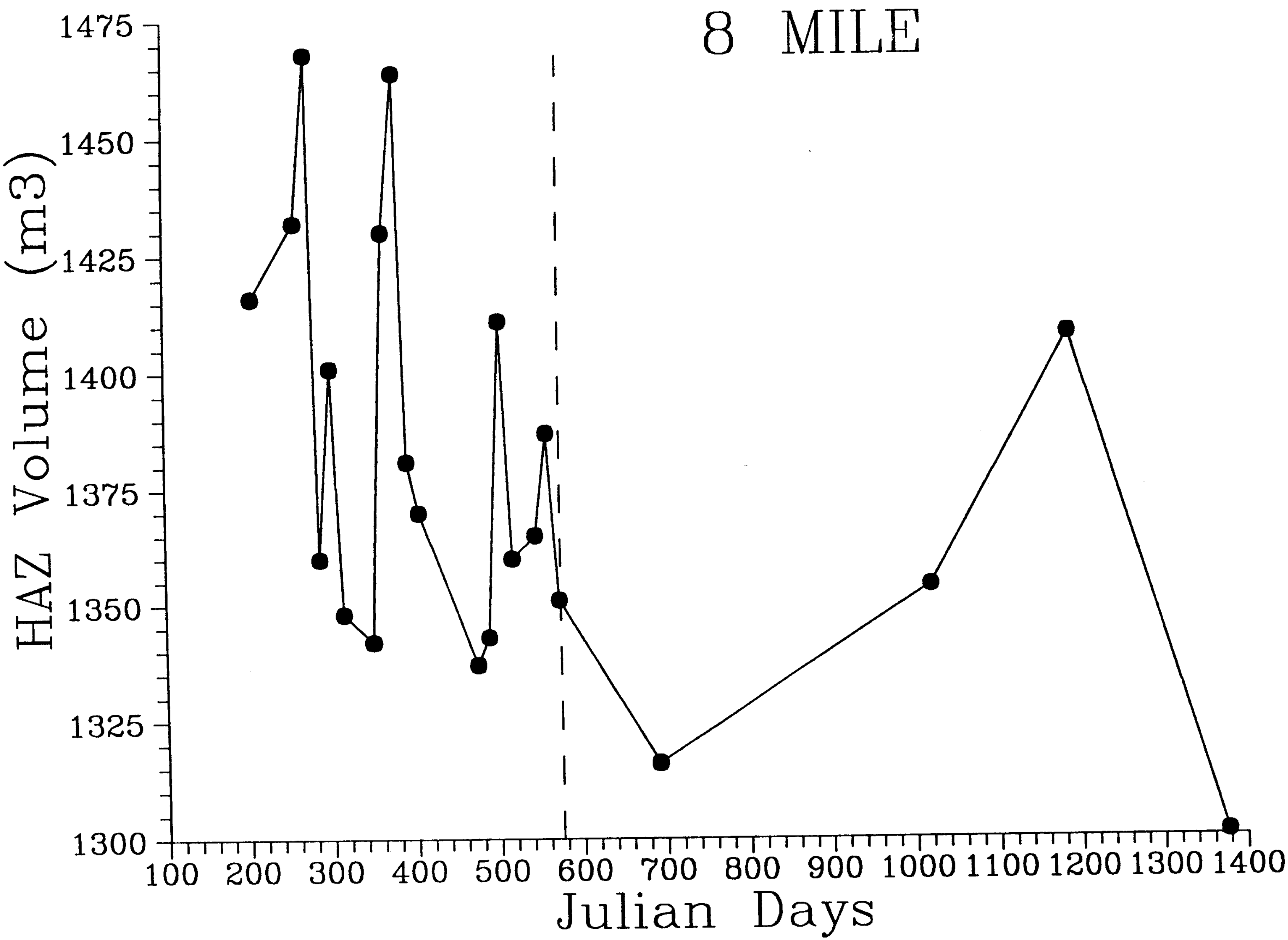

8 MILE PROFILE 4
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
97
96
95
94
93
92
91
90
95
100
105
110
115
120
125
130
135
11-22-91
10-15-92
04-01-93
10-08-93



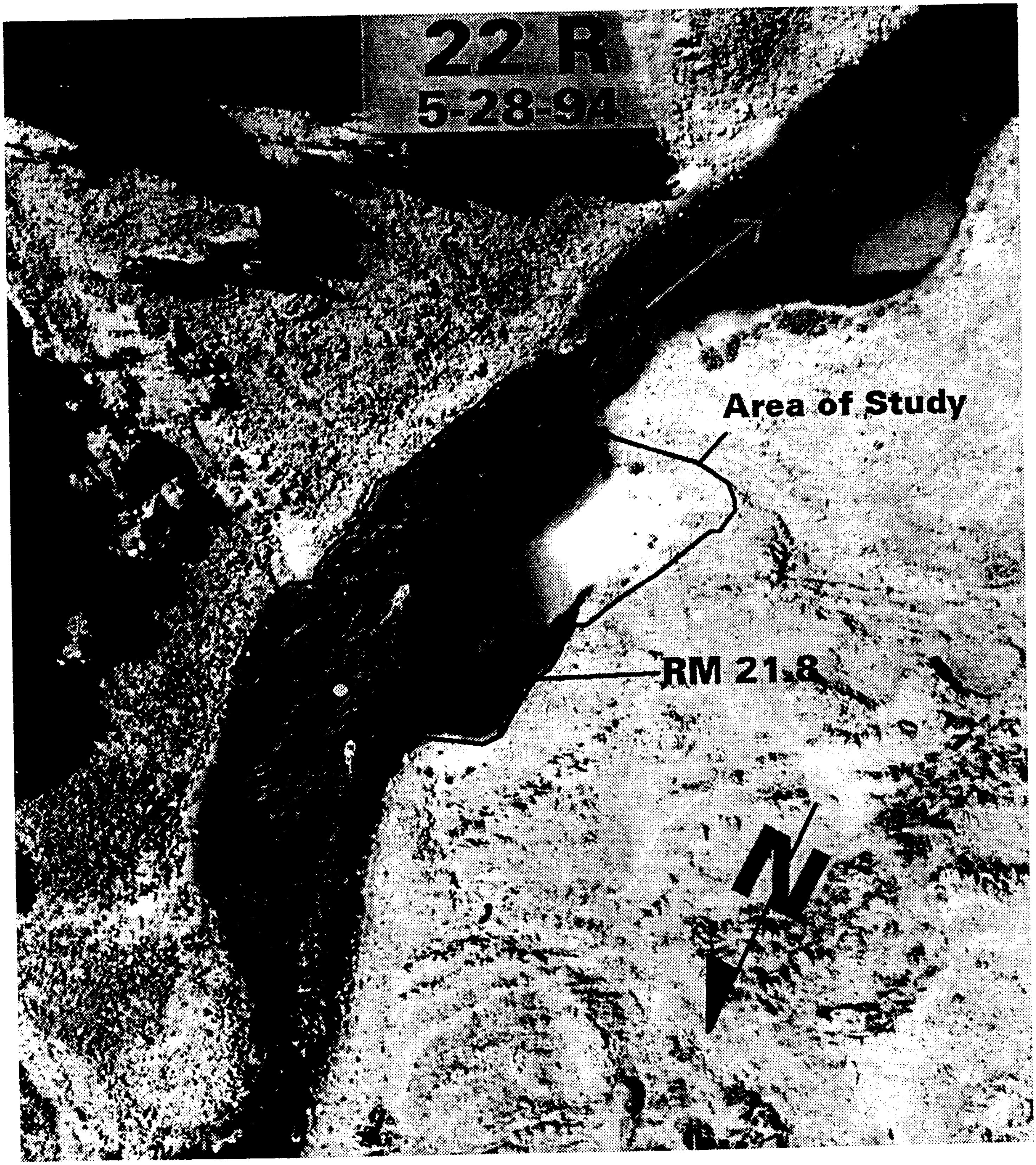
8 MILE PROFILE 5
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
11-22-91
10-15-92
04-01-93
10-08-93
97
96
95
94
93
92
91
90
95
100
105
110
115
120
125
130
135

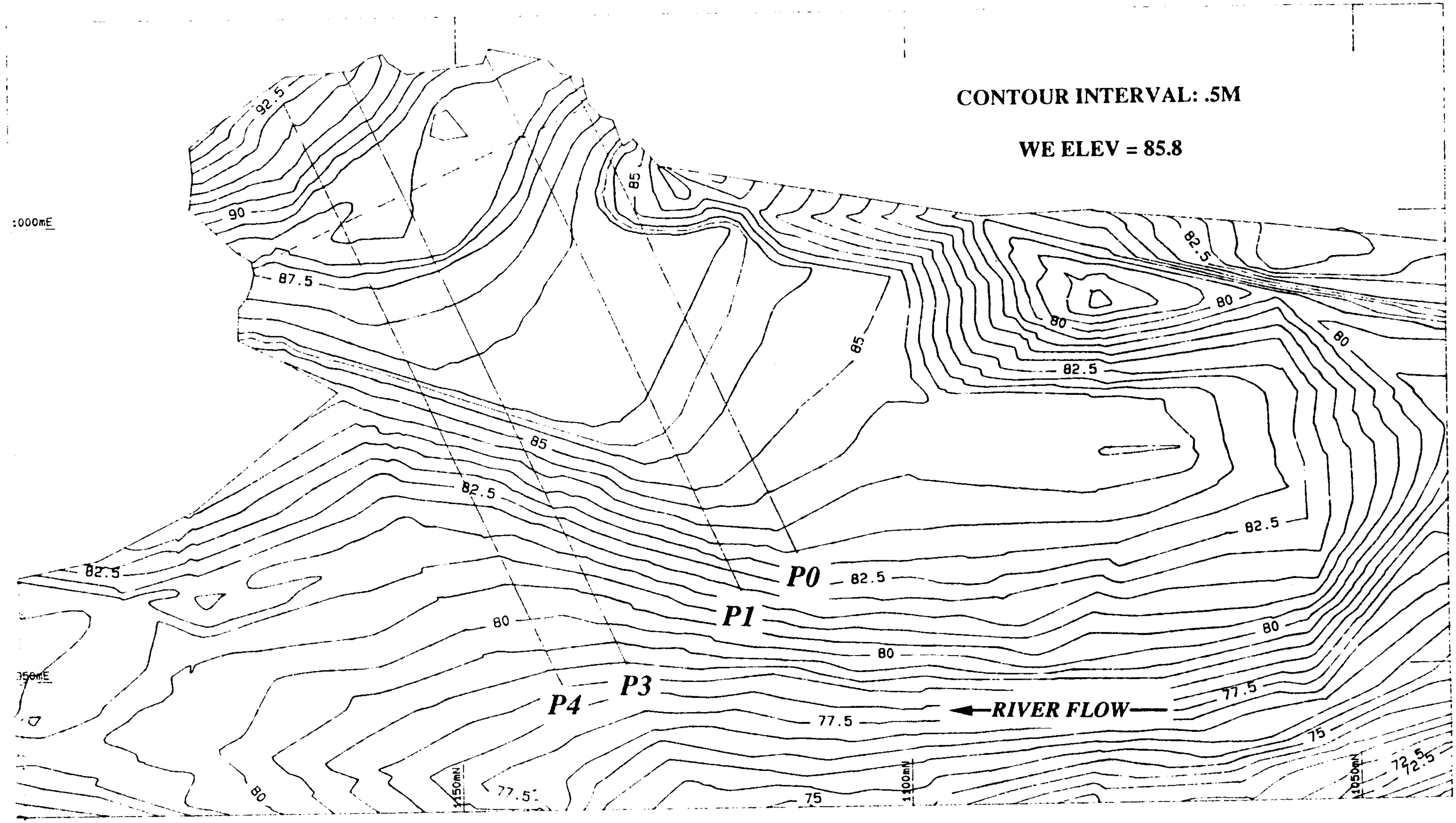

8 MILE PROFILE 6
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
97
96
95
94
93
92
91
90
95
100
105
110
115
120
125
130
135
11-22-91
10-15-92
04-01-93
10-08-93


8 MILE PROFILE 7
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
97
96
95
94
93
92
91
90
95
100
105
110
115
120
125
130
135
11-22-91
10-15-92
04-01-93
10-08-93



8 MILE
HAZ Volume (m3)
1475
1450
1425
1400
1375
1350
1325
1300
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days


22 R
5-28-94
Area of Study
RM 21.8
N

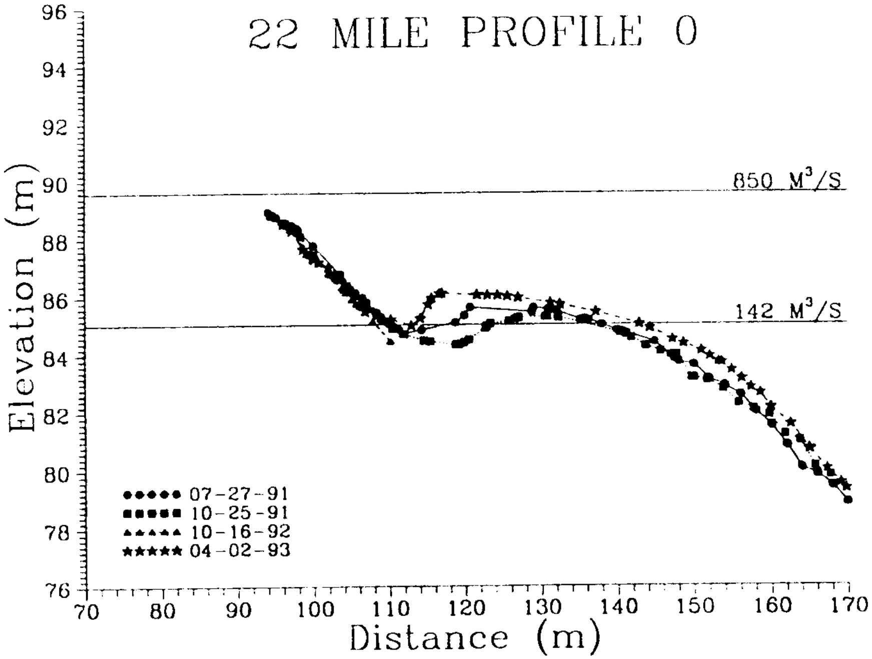


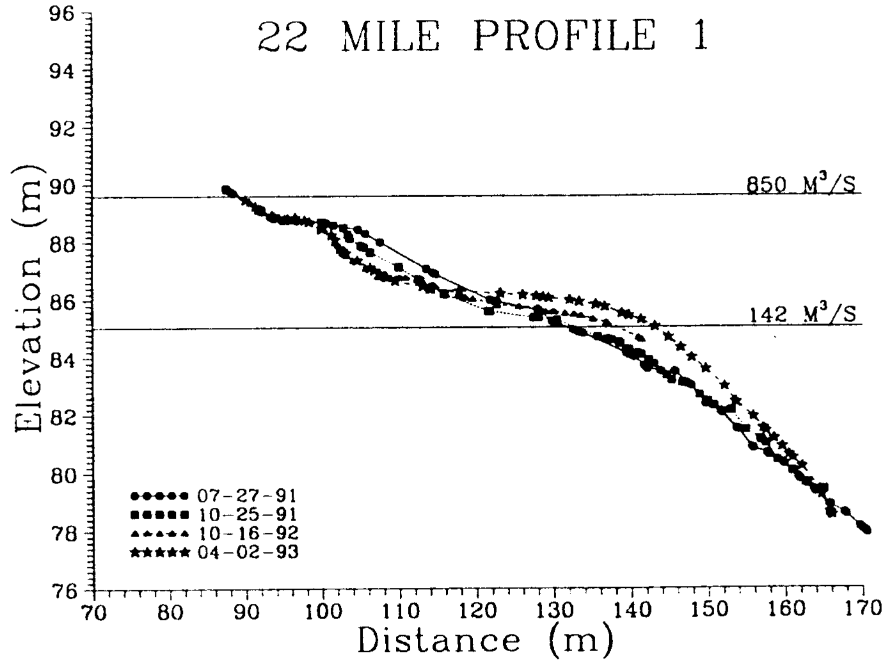
GCES BEACH SURVEY 06Z

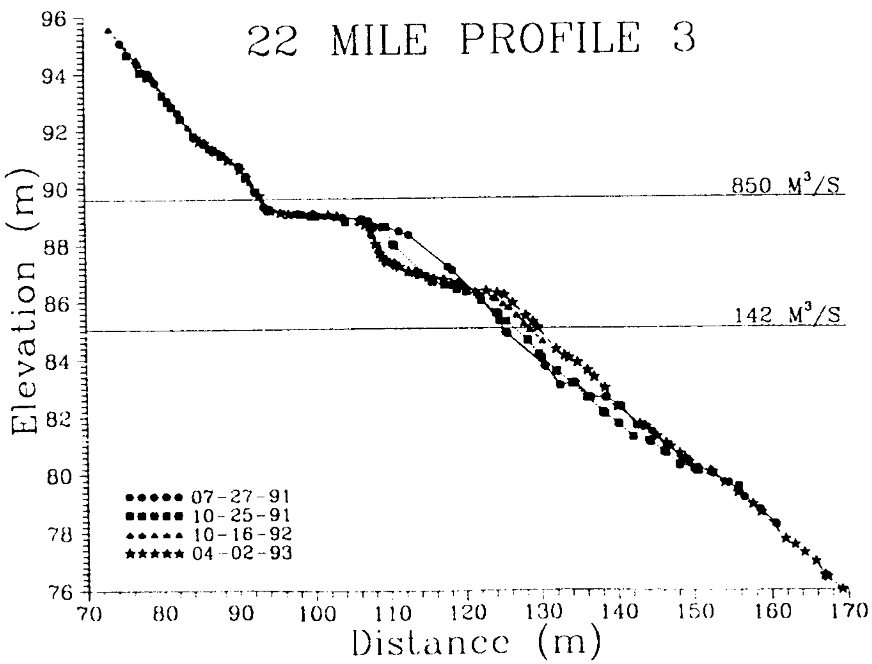
22R PROFILES

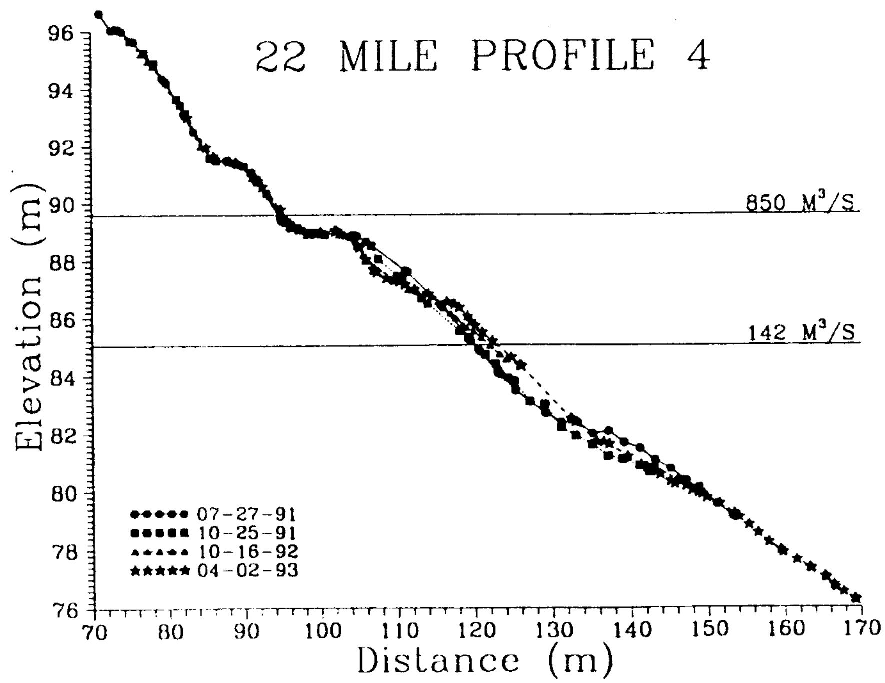
22 MILE 4-02-93

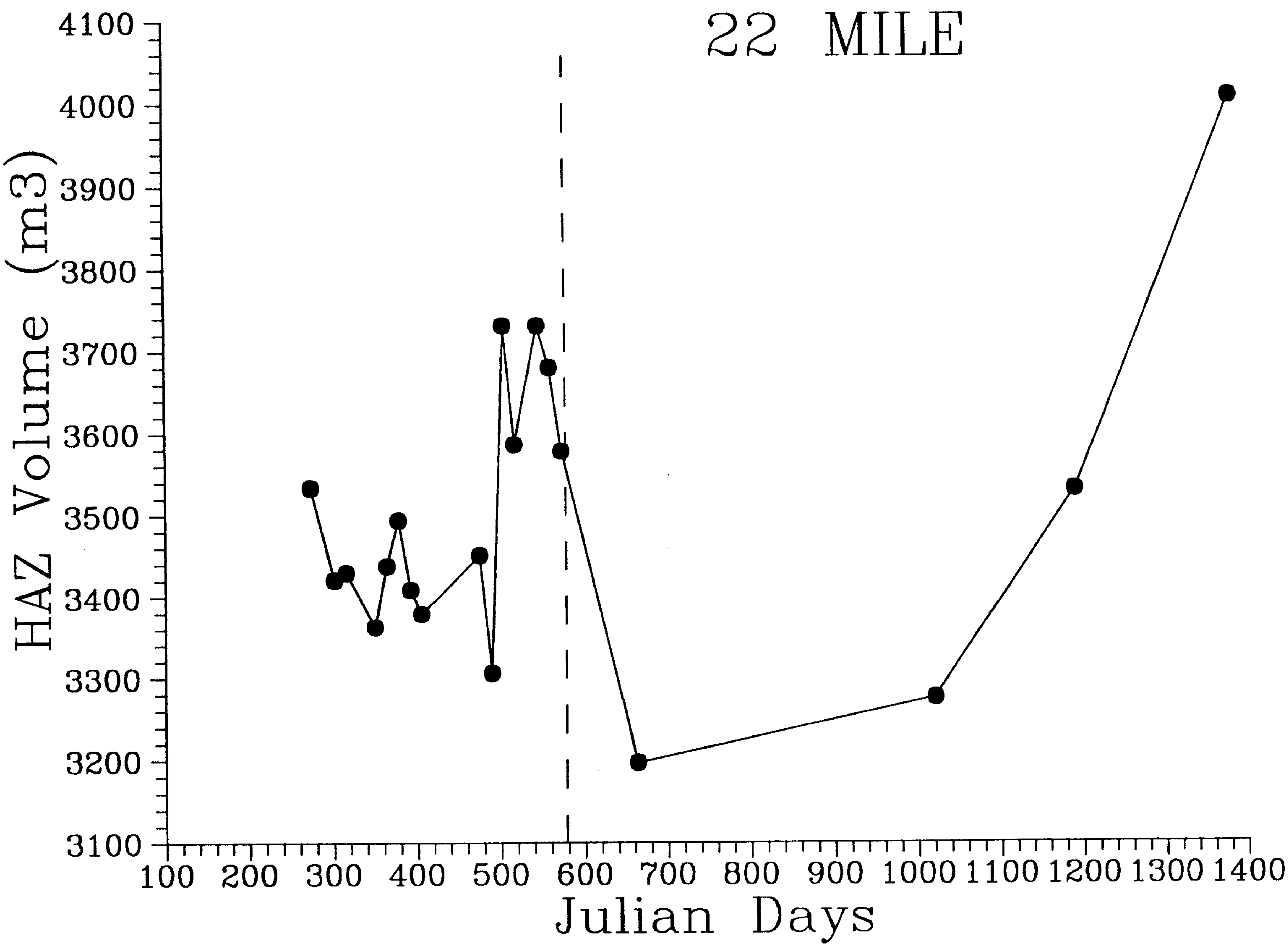
1: 400

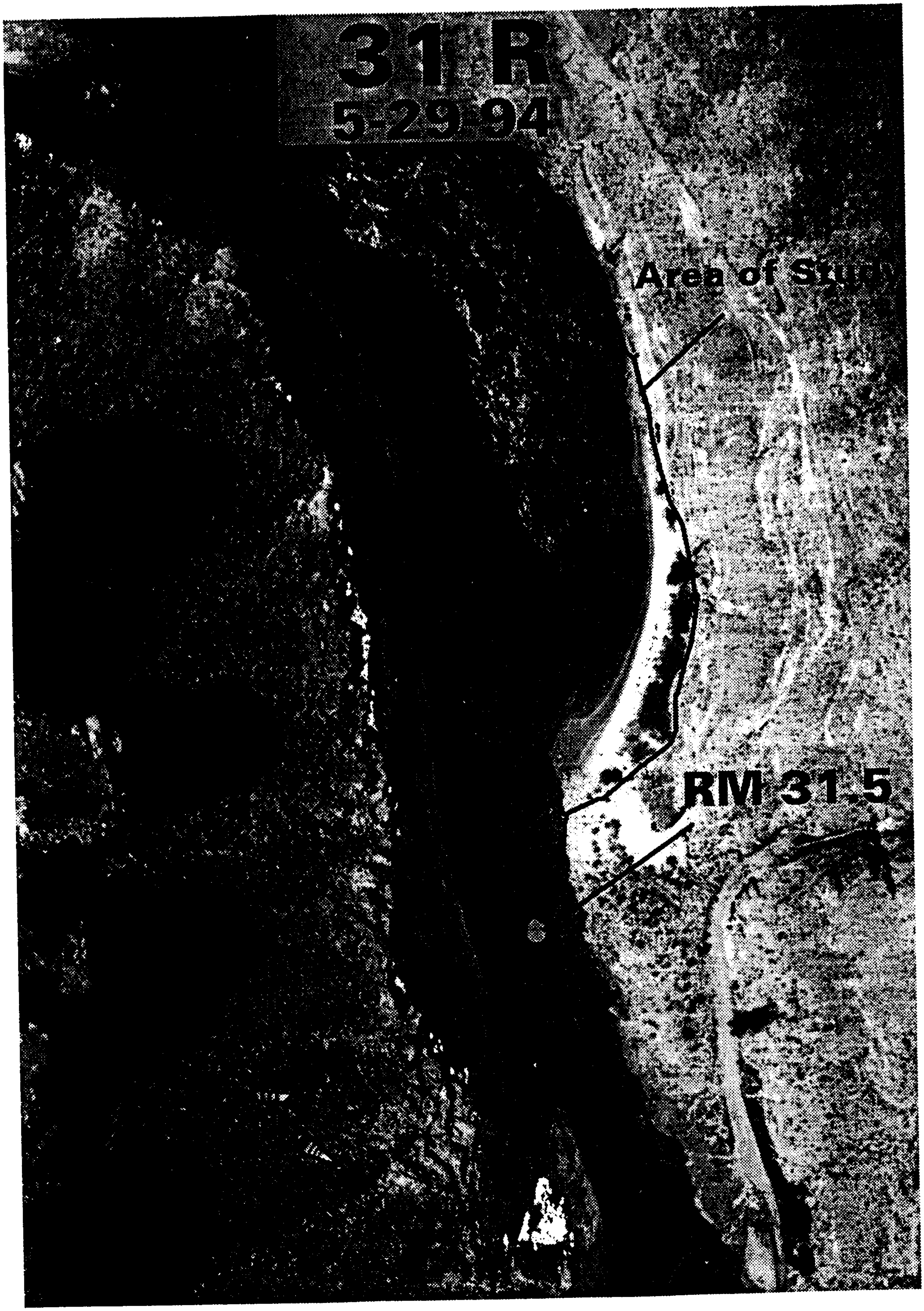

22 MILE PROFILE 0
850 M³/S
142 M³/S
07-27-91
10-25-91
10-16-92
04-02-93
Elevation (m)
Distance (m)

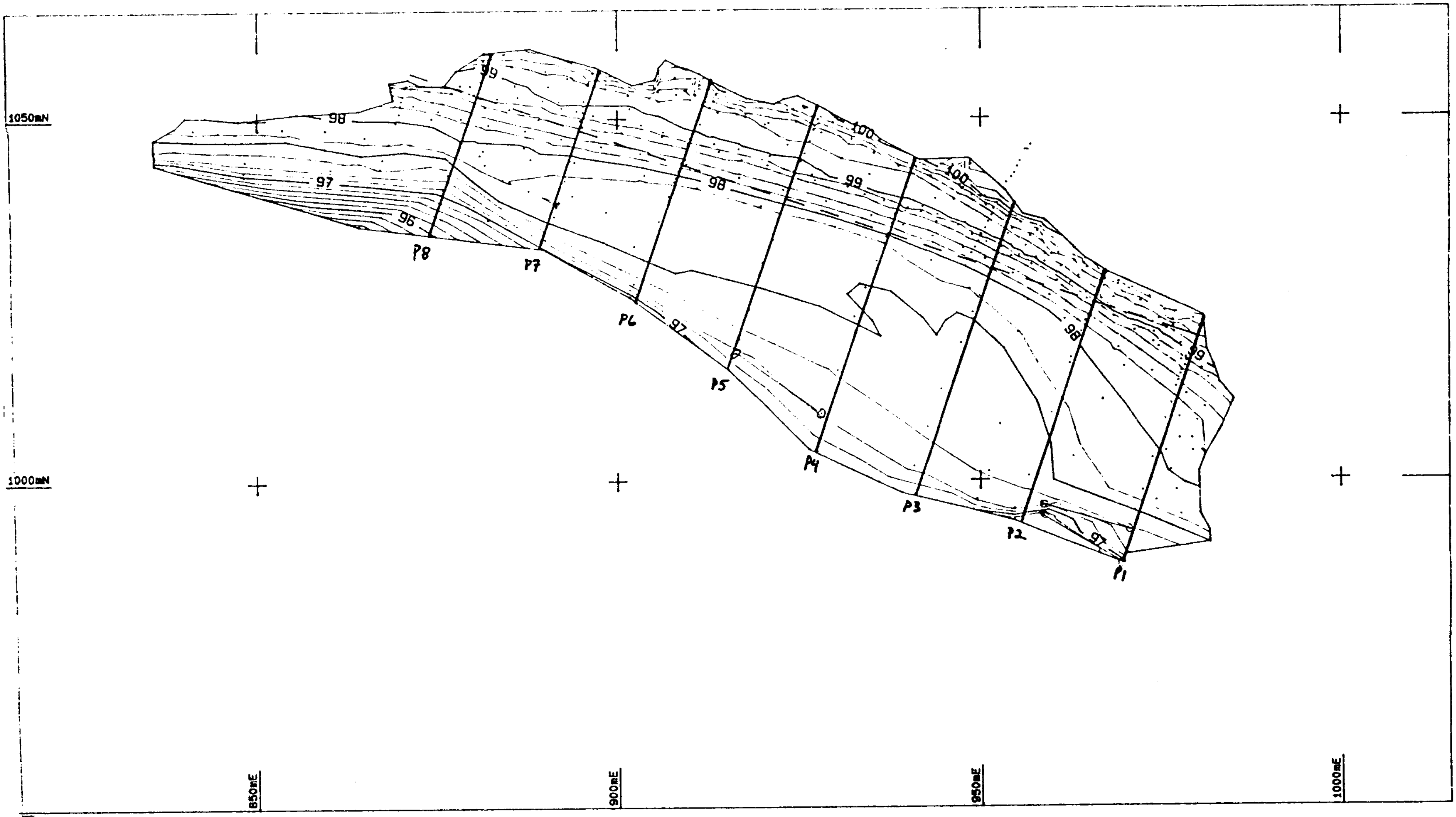

22 MILE PROFILE 1
850 M³/S
142 M³/S
07-27-91
10-25-91
10-16-92
04-02-93
Elevation (m)
Distance (m)


22 MILE PROFILE 3
850 M³/S
142 M³/S
07-27-91
10-25-91
10-16-92
04-02-93
Elevation (m)
Distance (m)

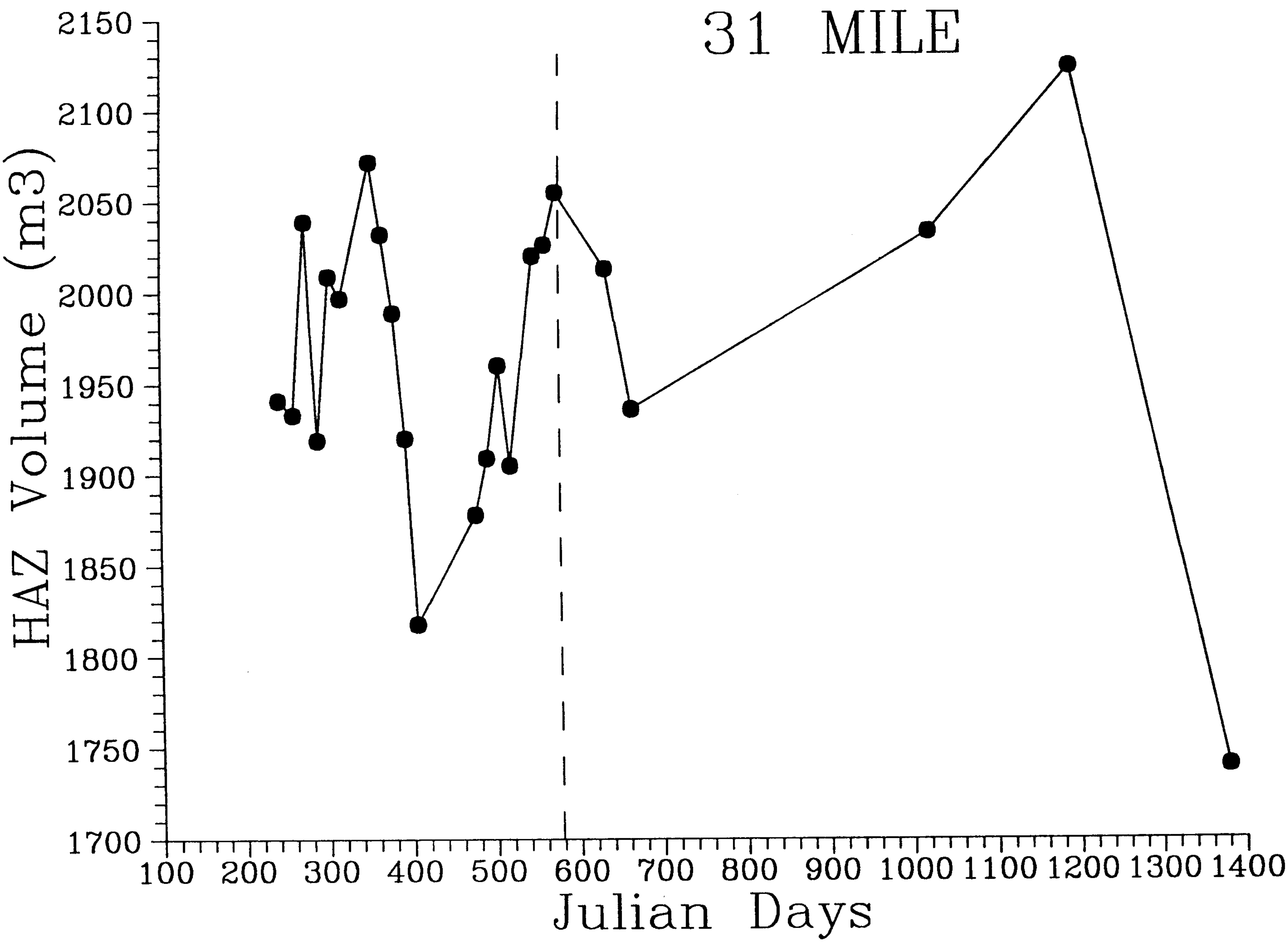

22 MILE PROFILE 4
850 M³/S
142 M³/S
07-27-91
10-25-91
10-16-92
04-02-93
Elevation (m)
Distance (m)


22 MILE
HAZ Volume (m3)
4100
4000
3900
3800
3700
3600
3500
3400
3300
3200
3100
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

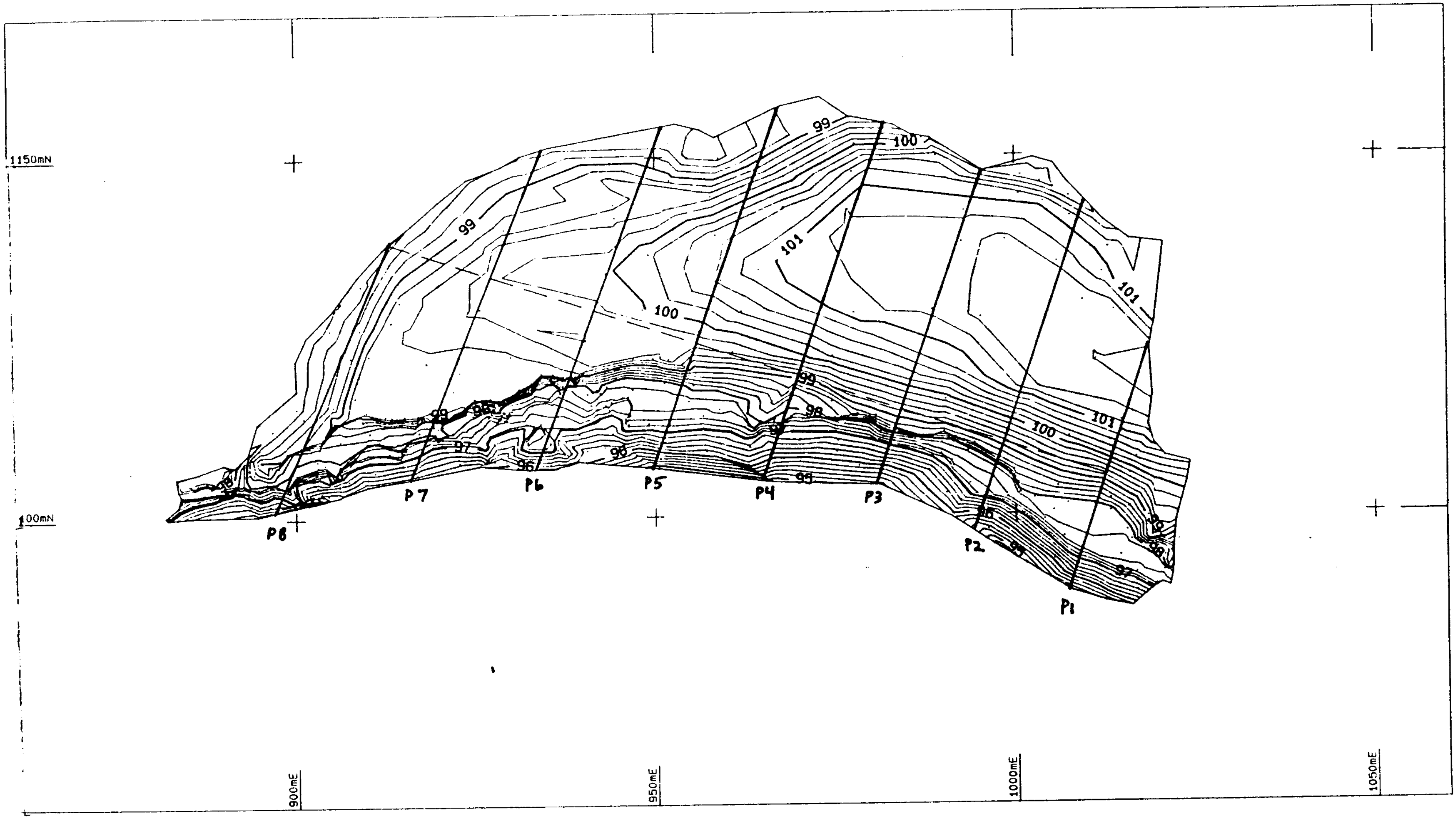

31 R
5 29 94
Area of Stu
RM 31.5



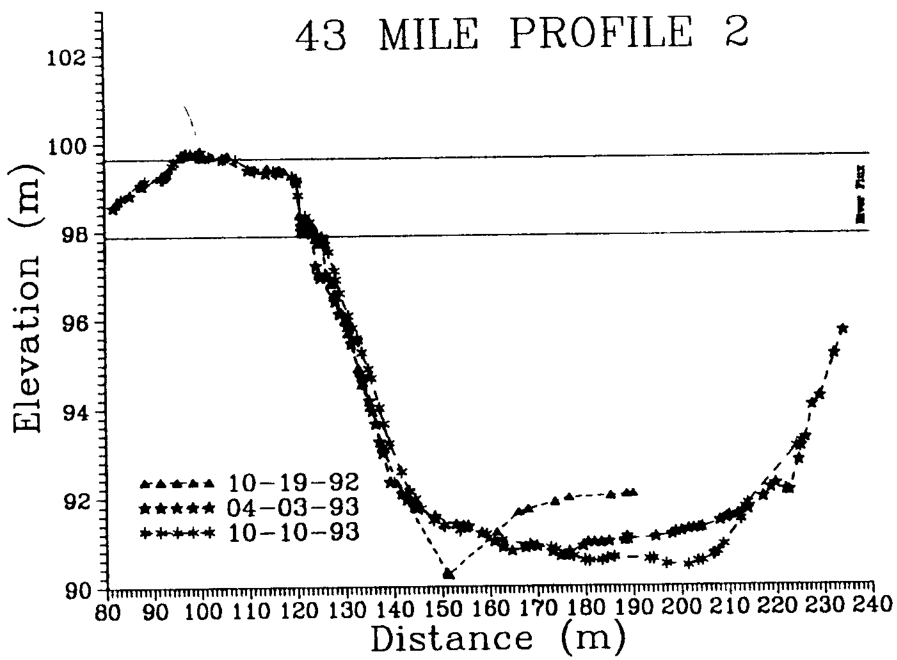
GCES BEACH SURVEY 08Z 31R-08V 31 MILE 4-03-93 1:500

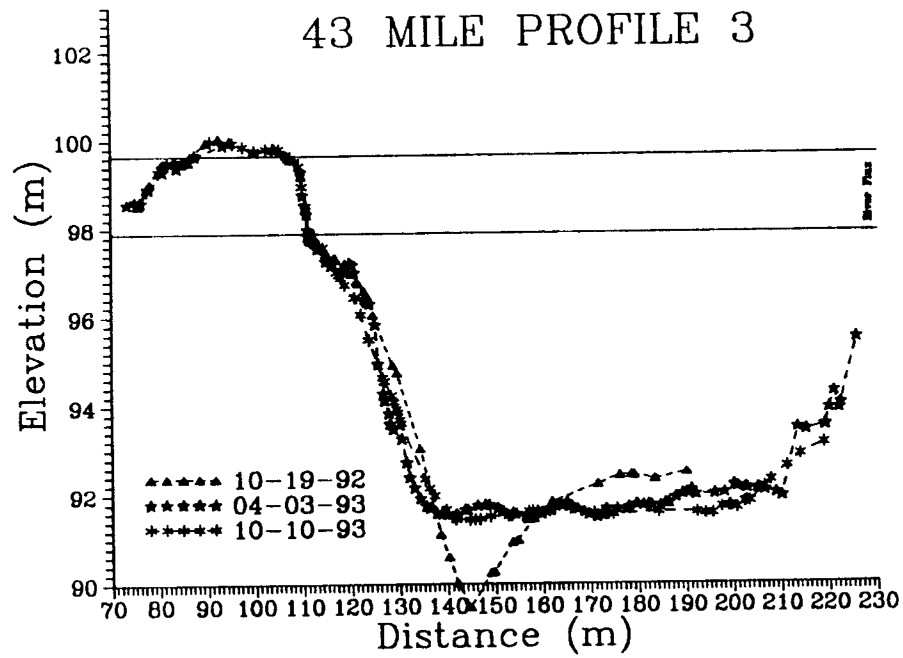

31 MILE
HAZ Volume (m3)
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days

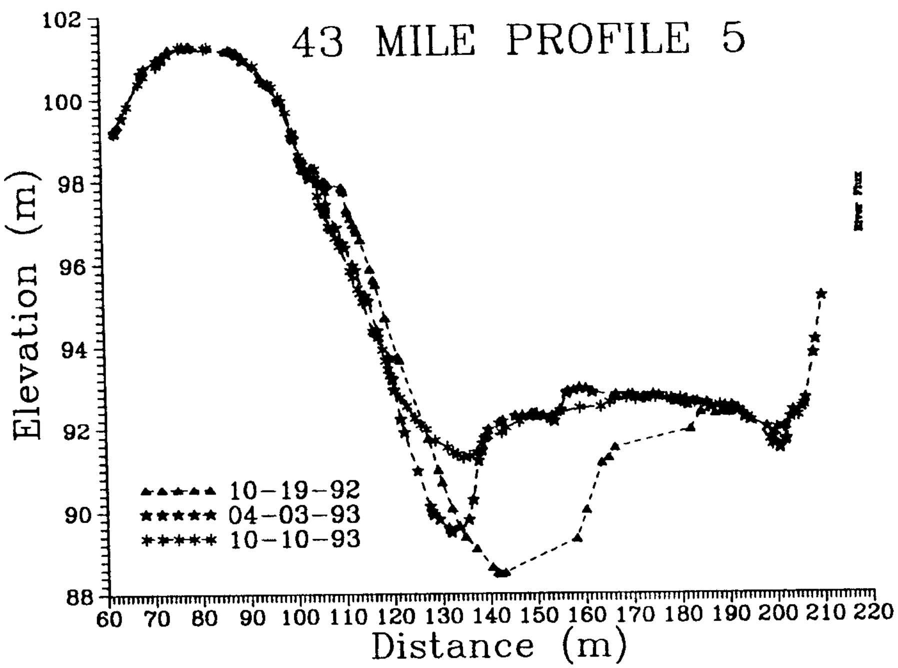

Area

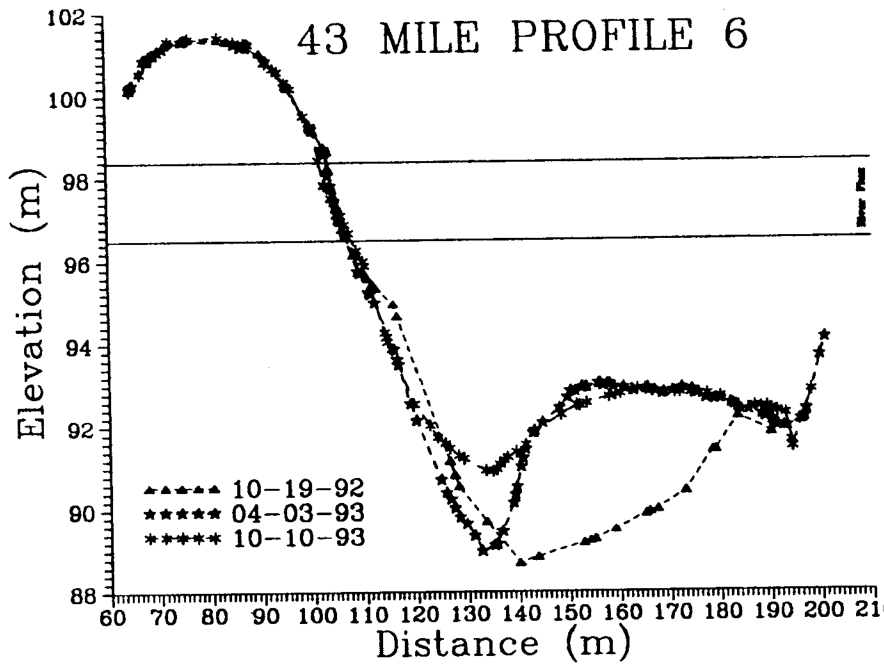


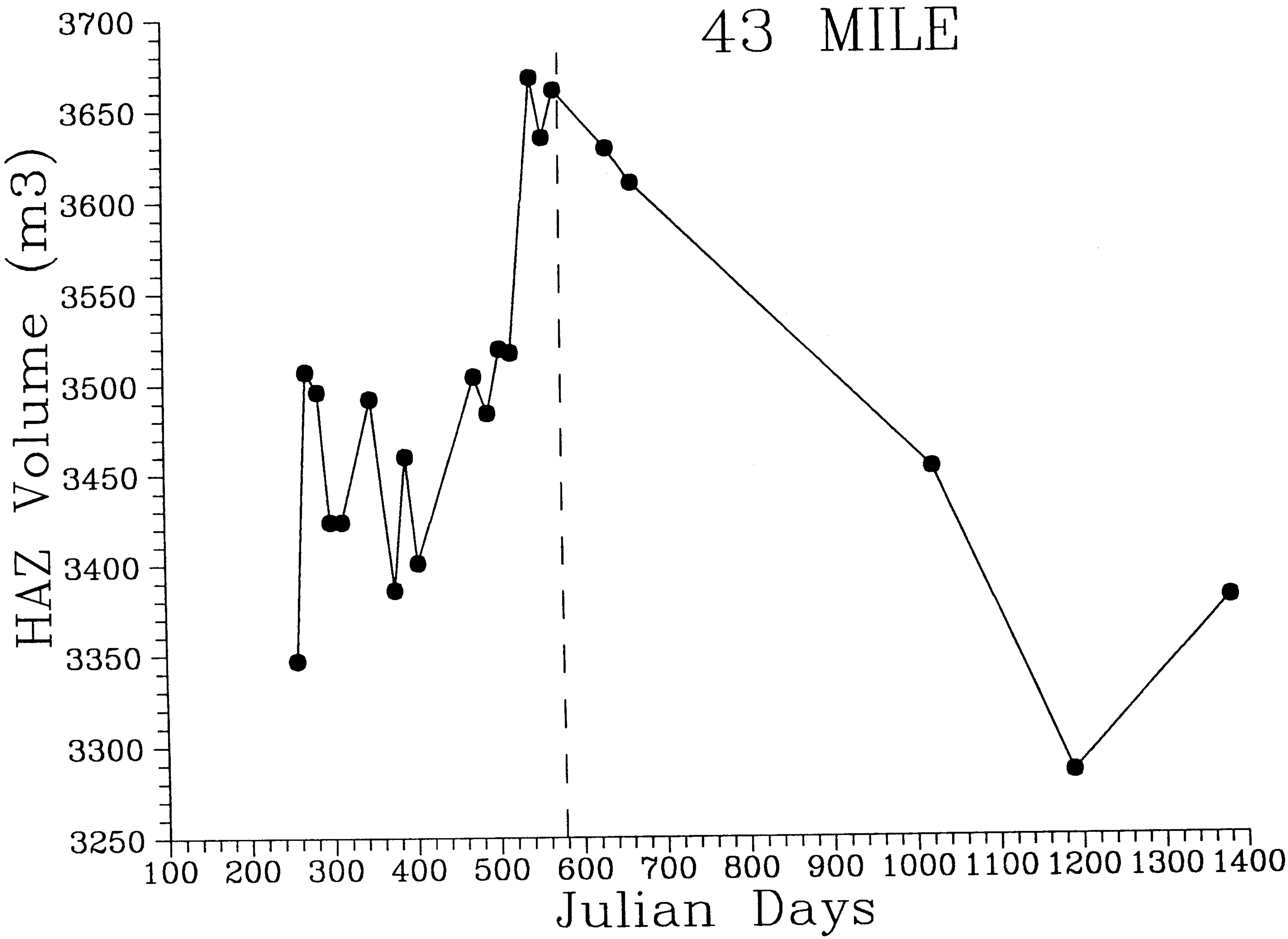
GCES BEACH SURVEY 10Z 43L-10Z 43L 04-03-93 1: 500


43 MILE PROFILE 2
Elevation (m)
Distance (m)
10-19-92
04-03-93
10-10-93

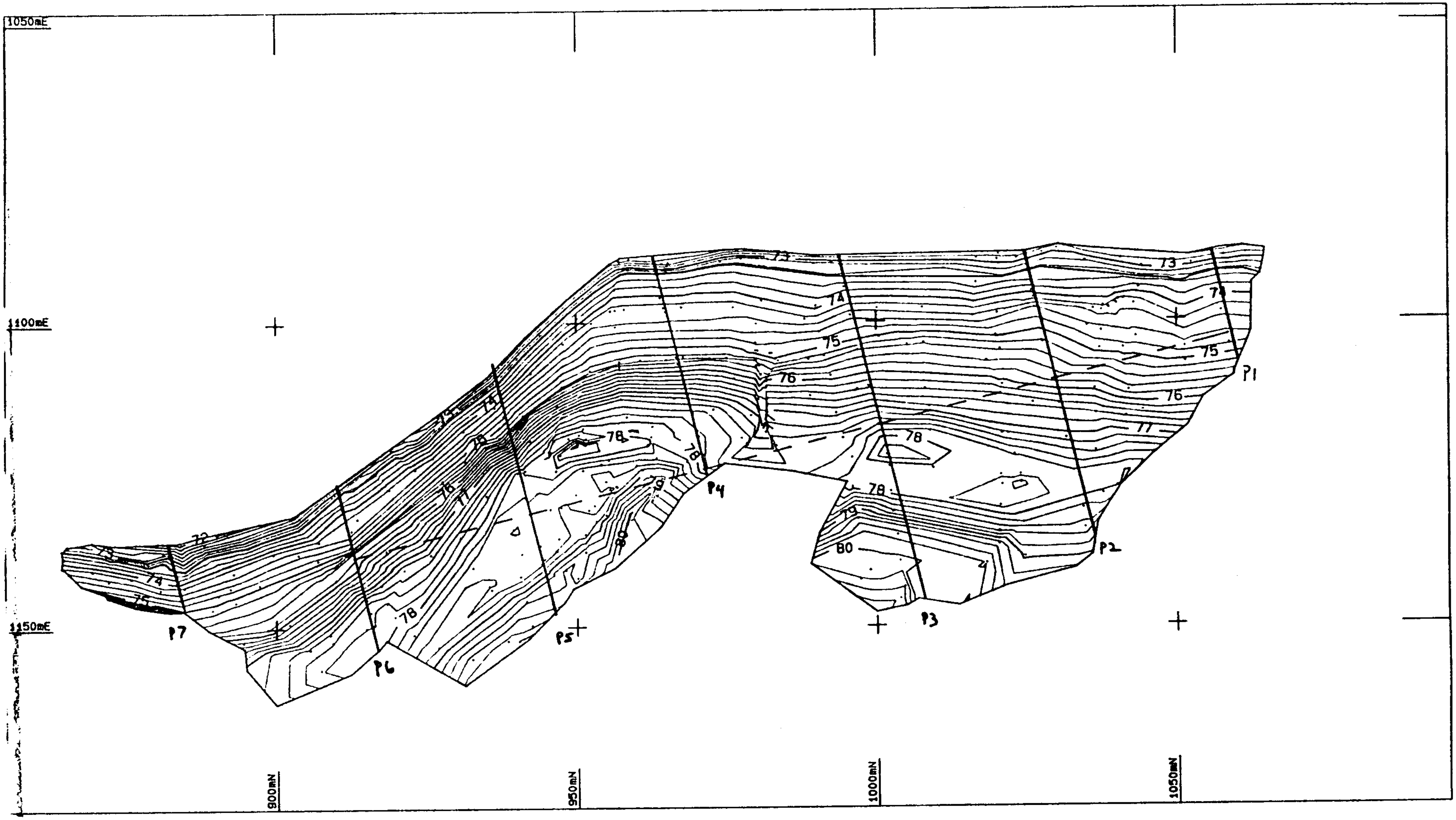

43 MILE PROFILE 3
Elevation (m)
Distance (m)
10-19-92
04-03-93
10-10-93


43 MILE PROFILE 5
Elevation (m)
Distance (m)
10-19-92
04-03-93
10-10-93


43 MILE PROFILE 6
Elevation (m)
Distance (m)
10-19-92
04-03-93
10-10-93


43 MILE
HAZ Volume (m3)
3700
3650
3600
3550
3500
3450
3400
3350
3300
3250
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

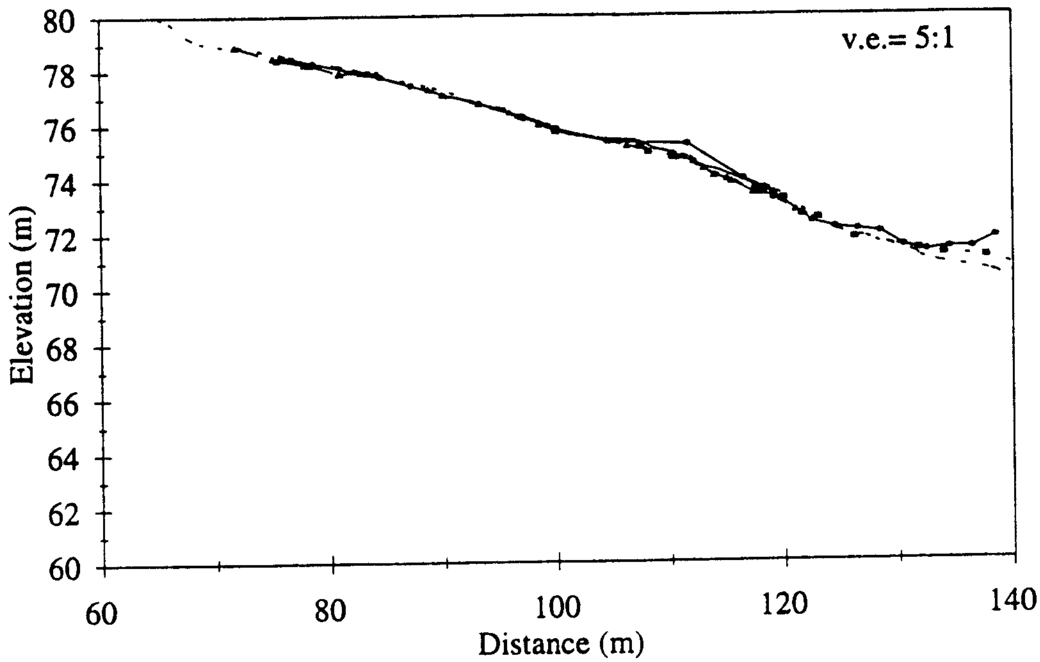

Area of Study
RM 44.5



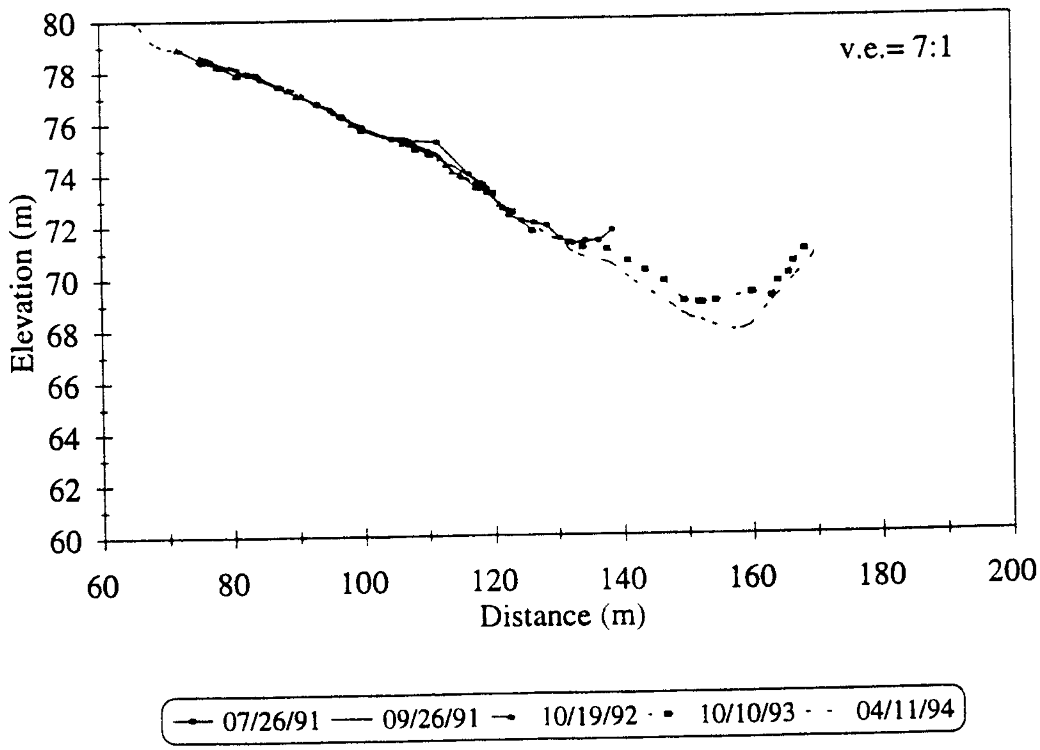
GCES BEACH SURVEY 11Y 45L-11Y 45 MILE 10-19-92 1: 600

45 Mile

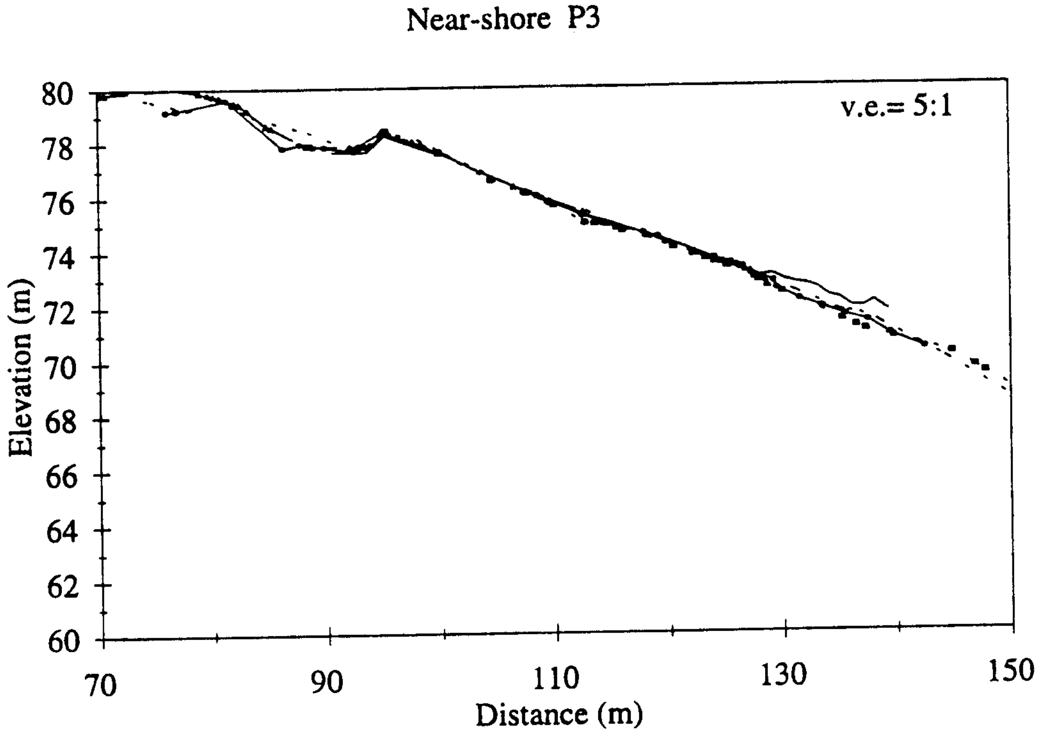
Near-shore P2

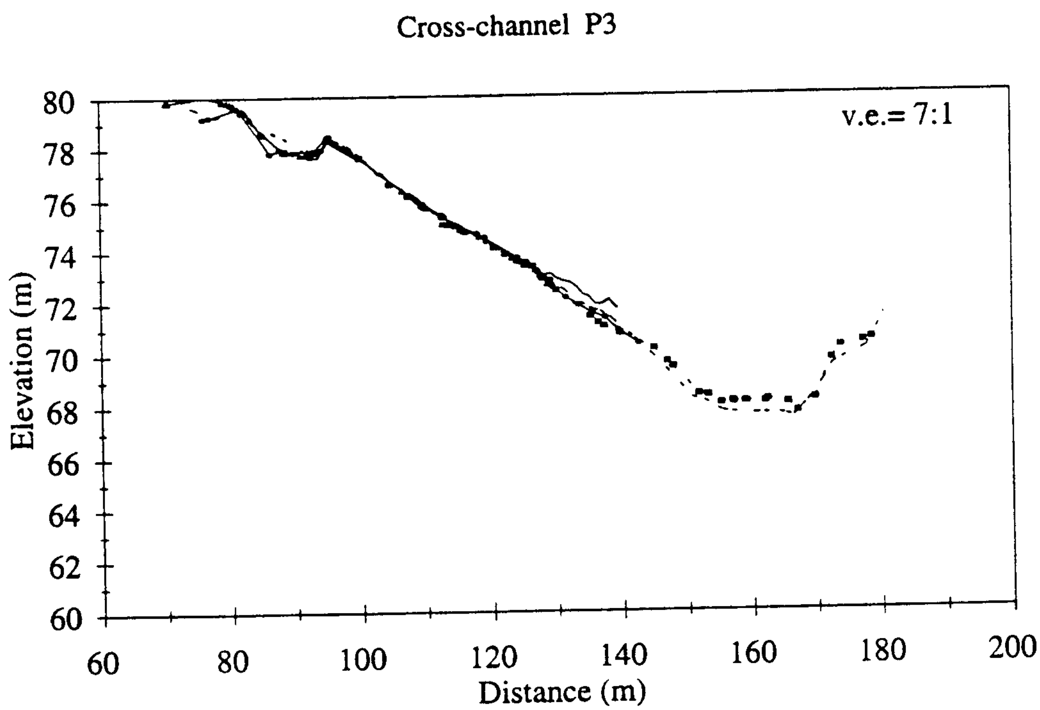


Cross-channel P2



45 Mile

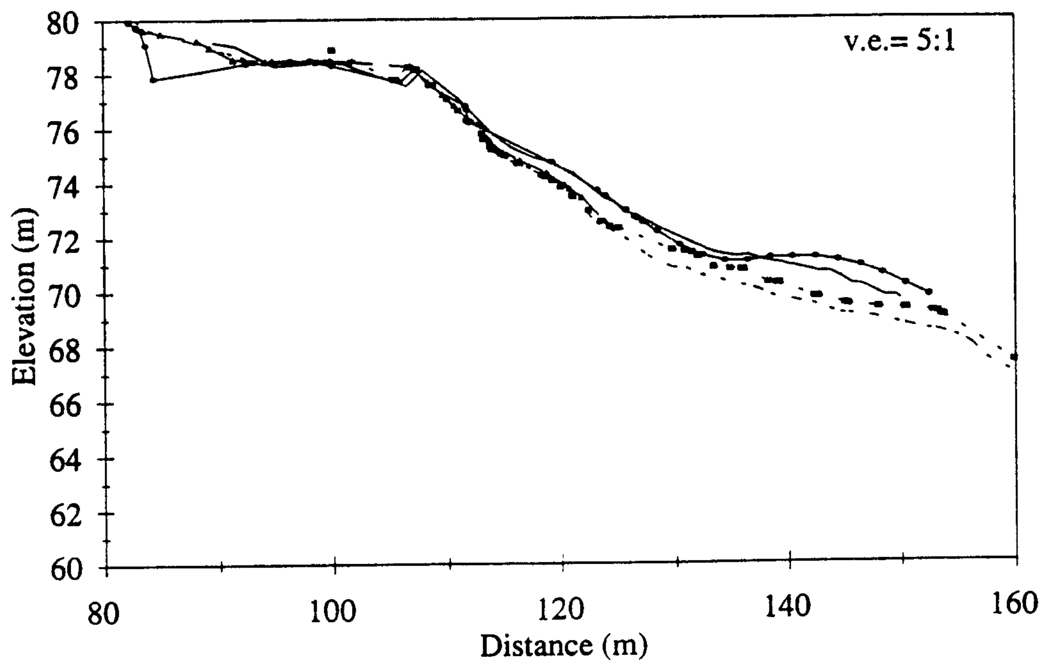




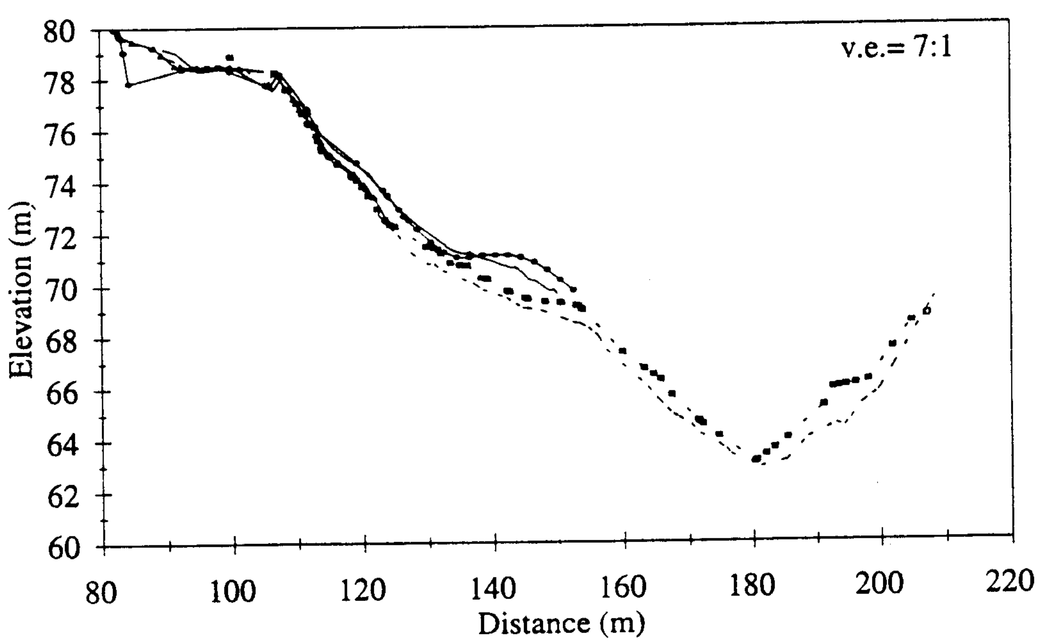
07/26/91 — 09/26/91 — 10/19/92 · 10/10/93 · · 04/11/94

45 Mile

Near-shore P5



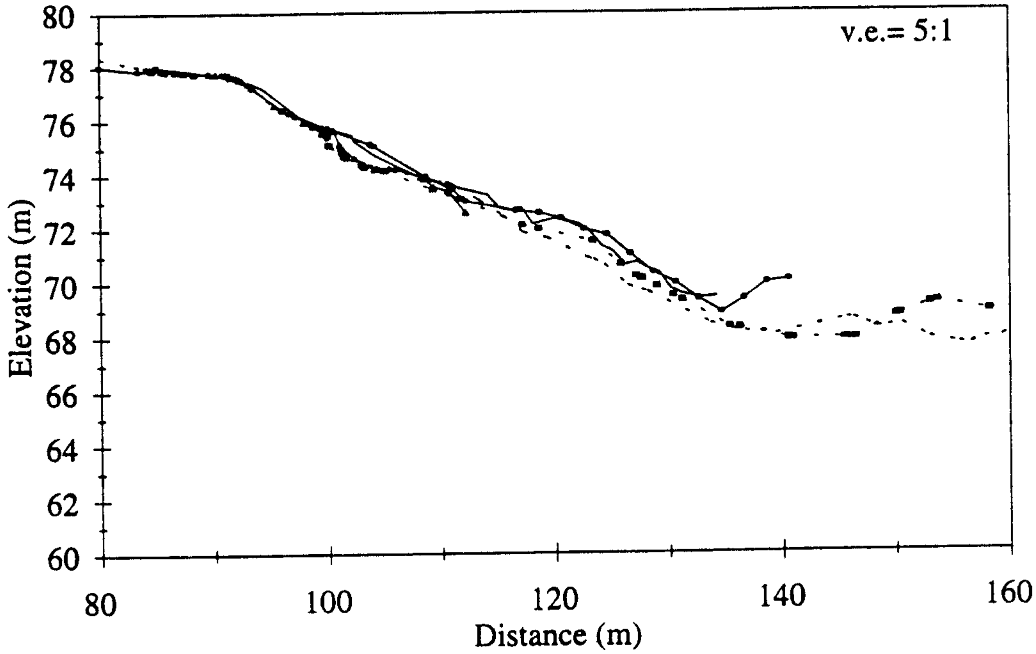
Cross-channel P5



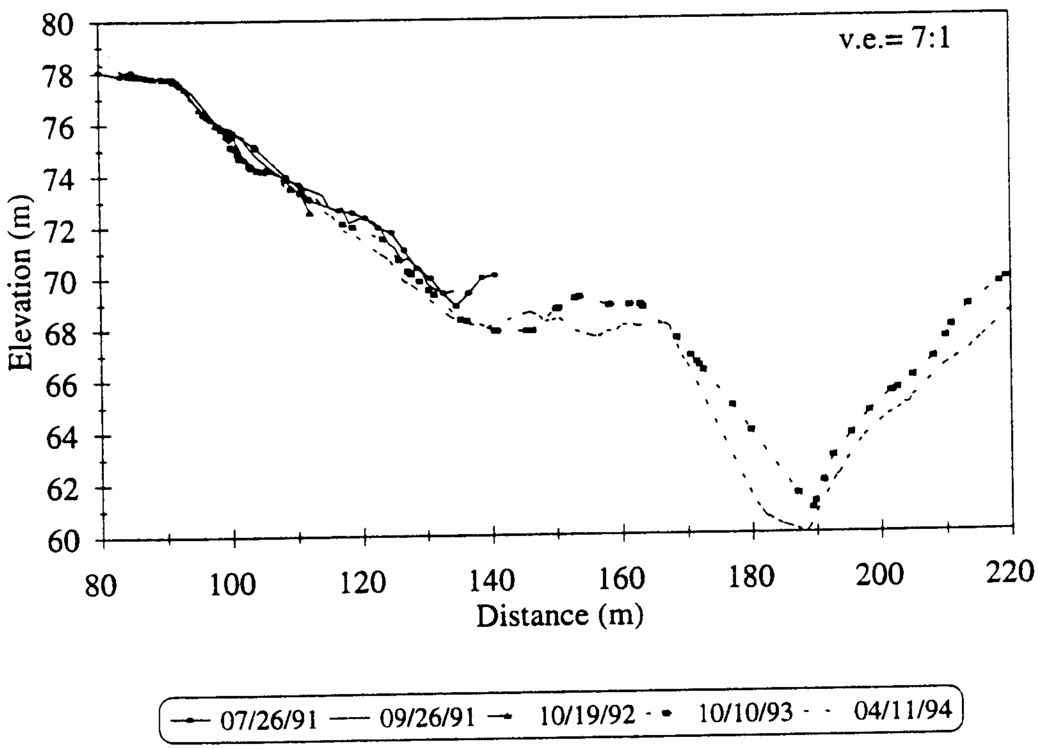
07/26/91 — 09/26/91 — 10/19/92 — 10/10/93 - - 04/11/94

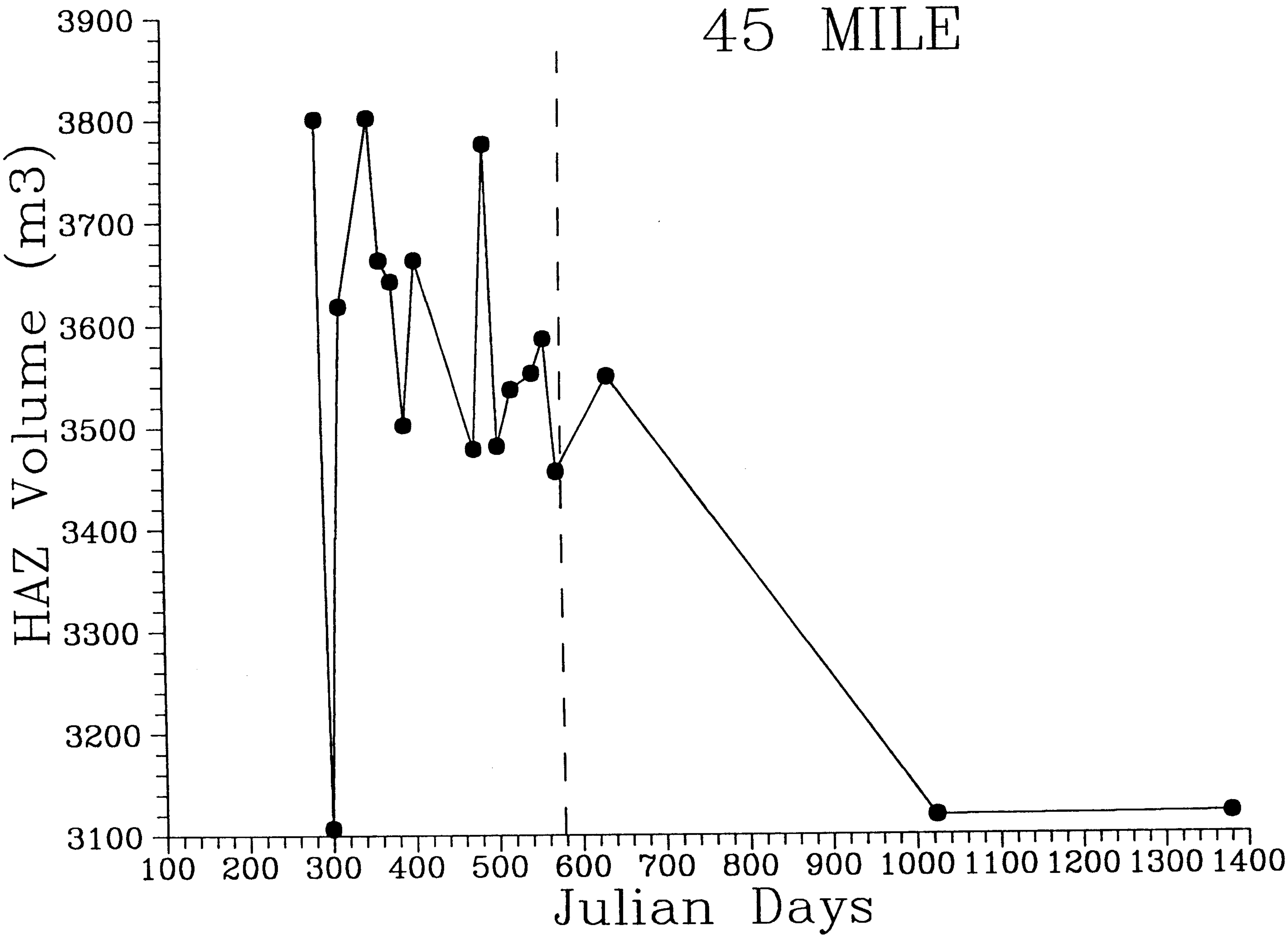
45 Mile

Near-shore P6

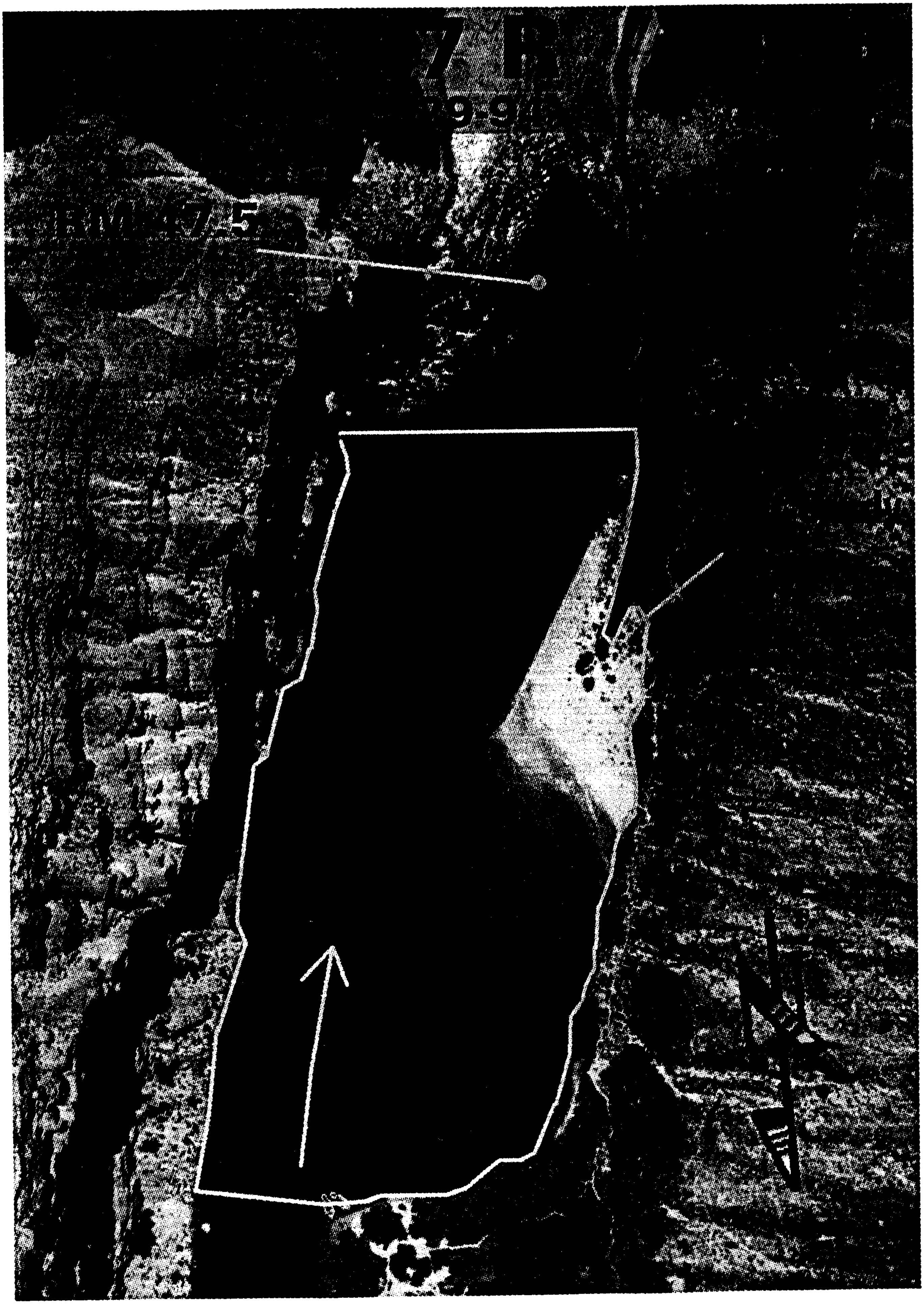


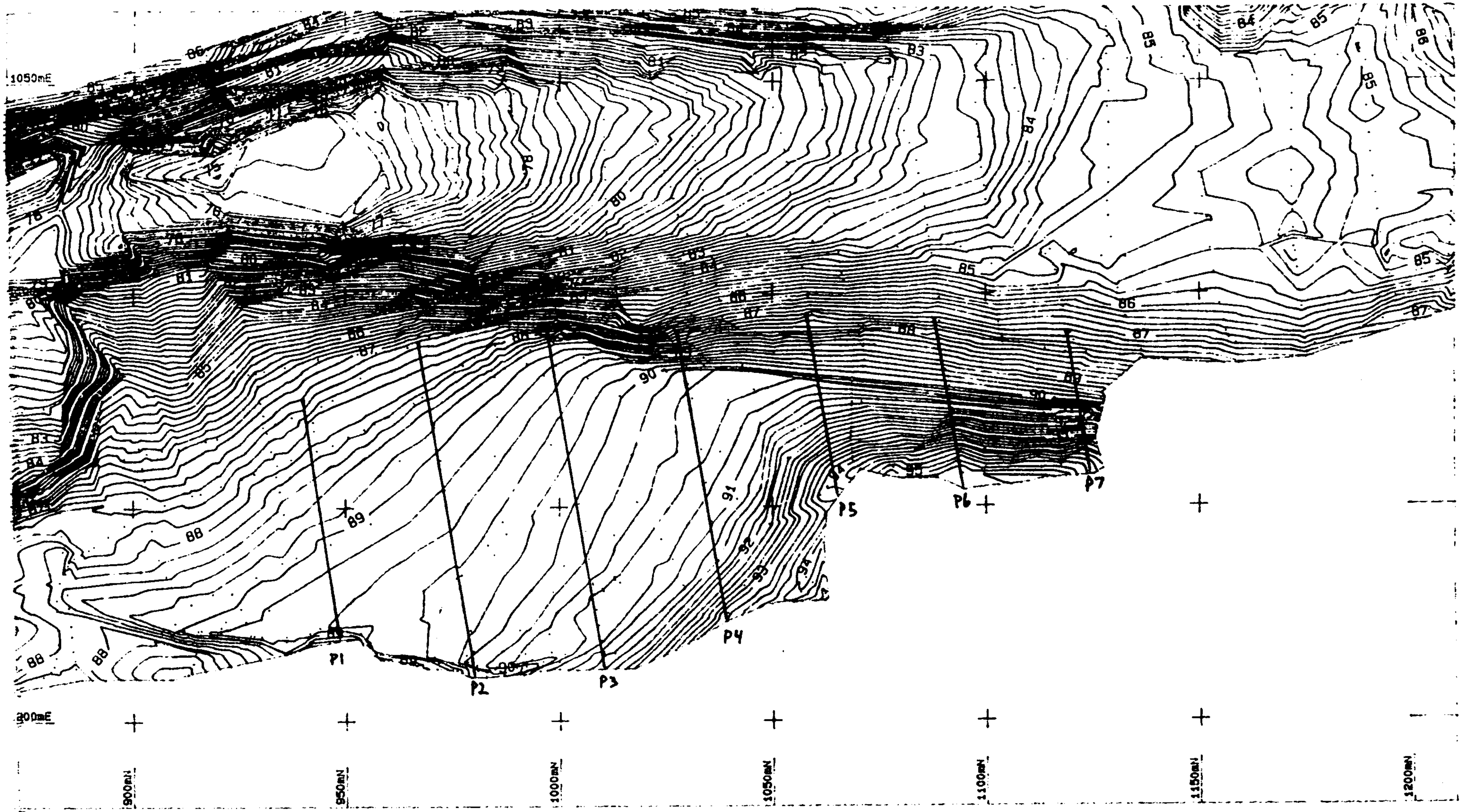
Cross-channel P6





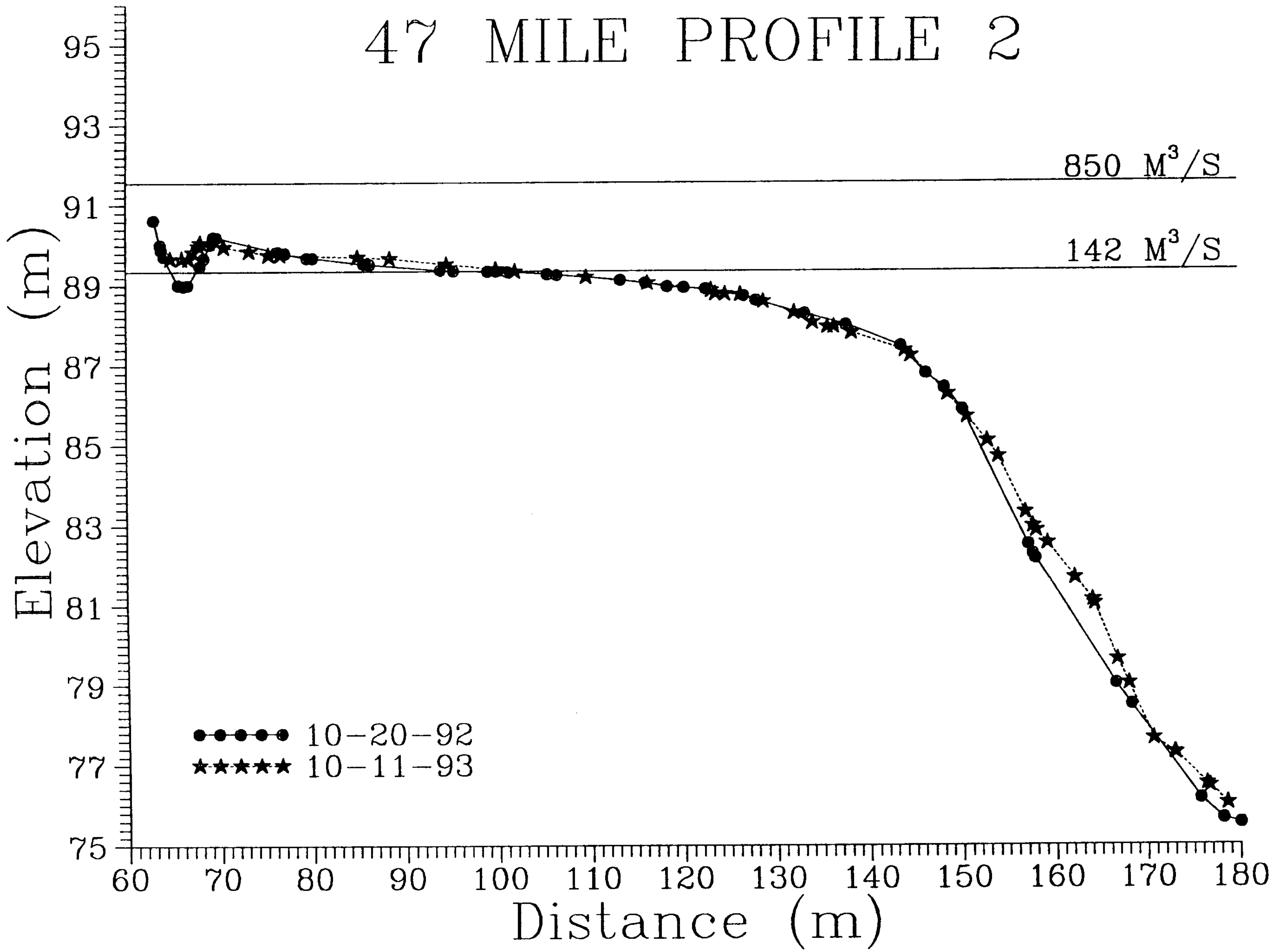
45 MILE
HAZ Volume (m3)
3900
3800
3700
3600
3500
3400
3300
3200
3100
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days

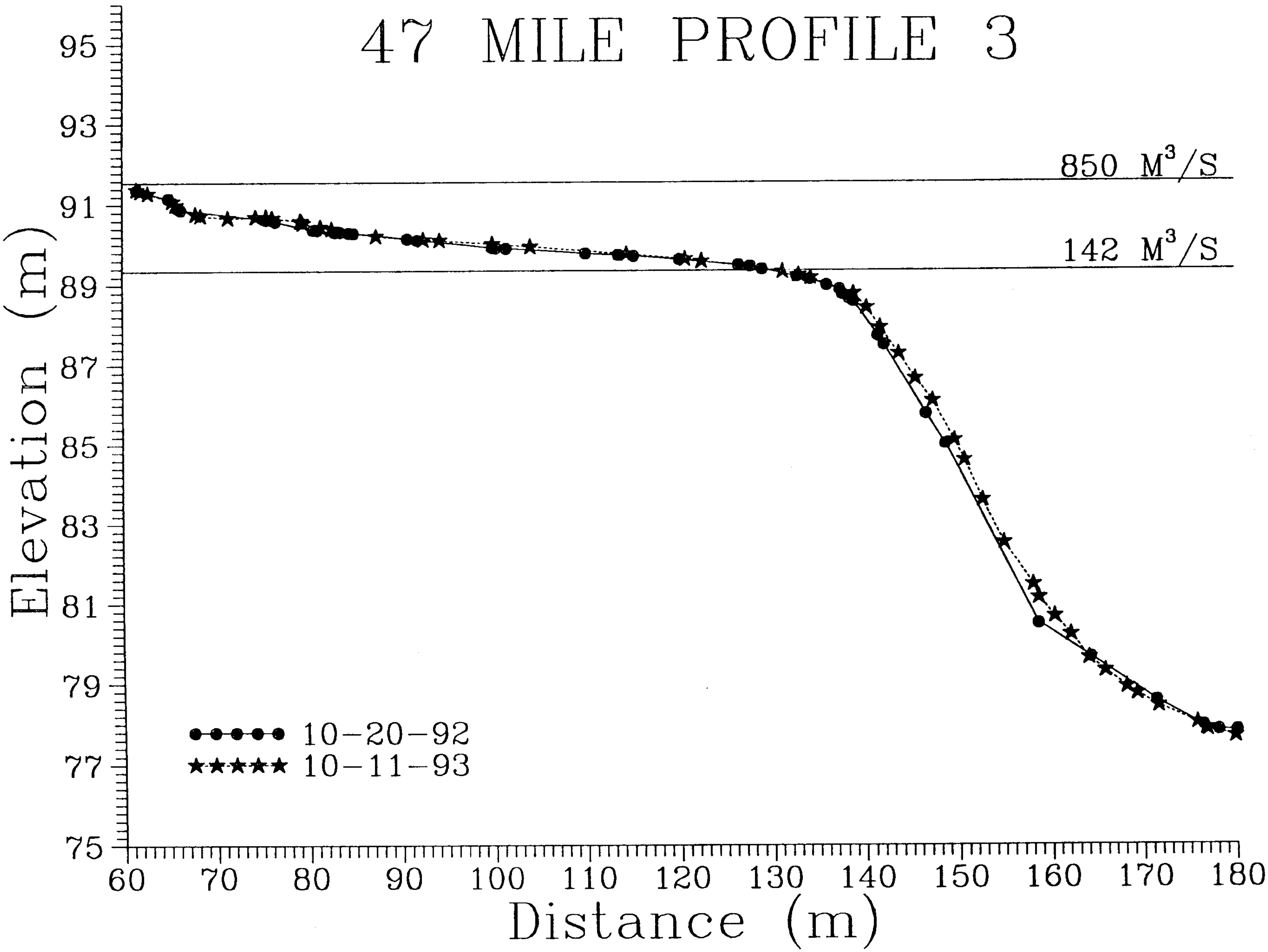




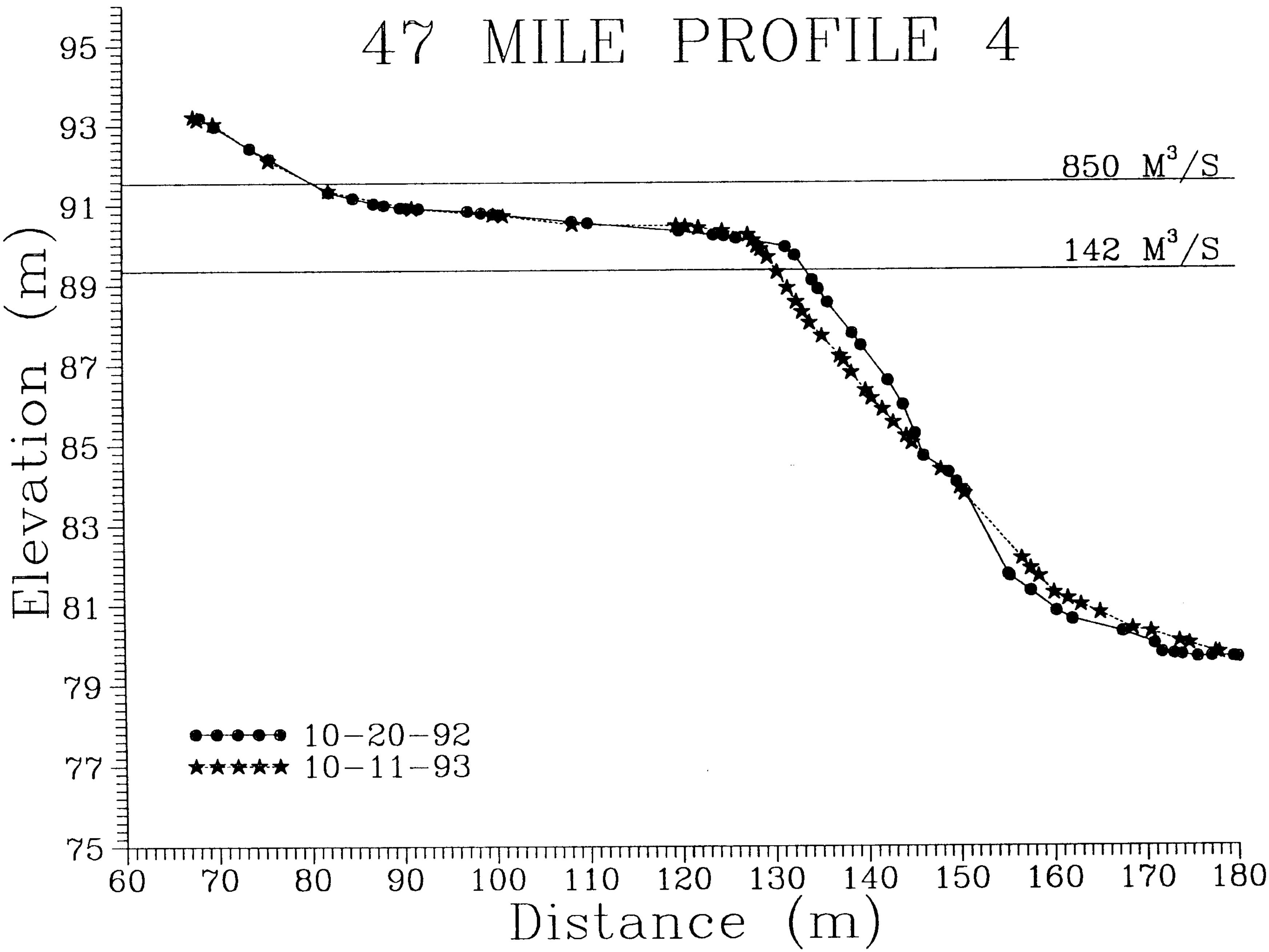
47R-B12

GOES BEACH SURVEY B12 47.1R 10-11-93 1: 850

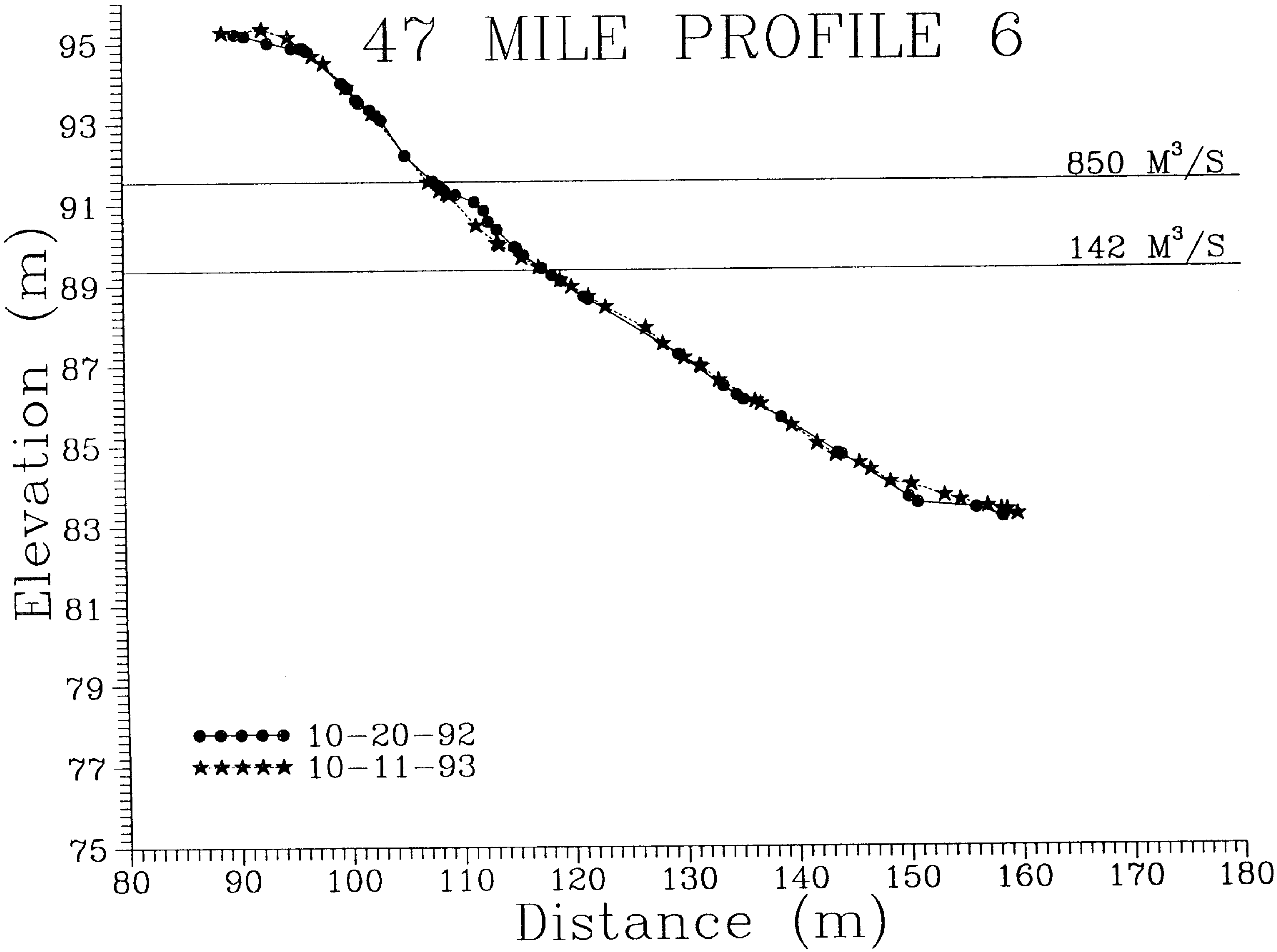

47 MILE PROFILE 2
850 M³/S
142 M³/S
10-20-92
10-11-93
Elevation (m)
Distance (m)
95
93
91
89
87
85
83
81
79
77
75
60
70
80
90
100
110
120
130
140
150
160
170
180



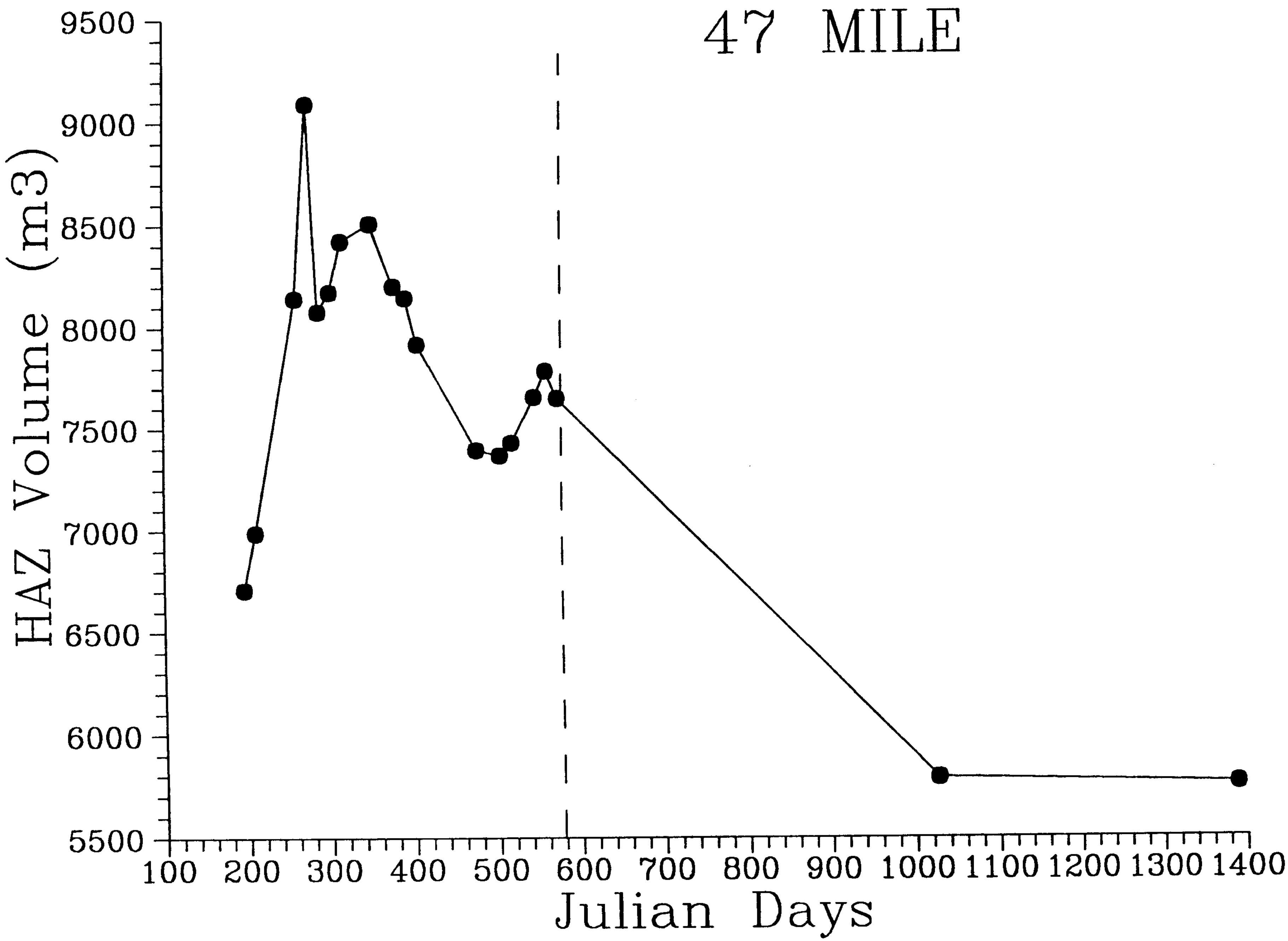
47 MILE PROFILE 3
850 M³/S
142 M³/S
Elevation (m)
95
93
91
89
87
85
83
81
79
77
75
Distance (m)
60
70
80
90
100
110
120
130
140
150
160
170
180
10-20-92
10-11-93



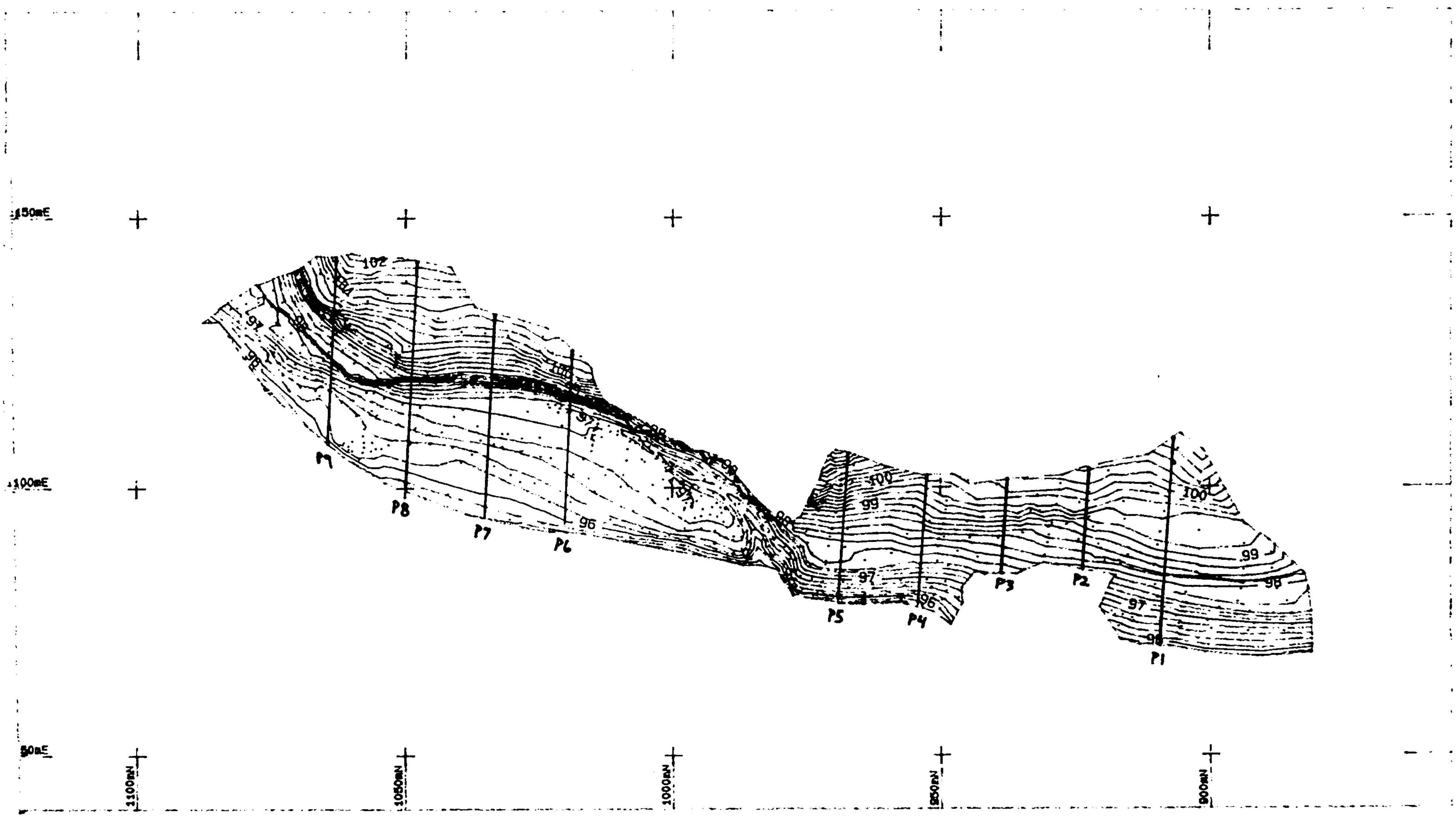
47 MILE PROFILE 4
850 M³/S
142 M³/S
10-20-92
10-11-93
Elevation (m)
Distance (m)
95
93
91
89
87
85
83
81
79
77
75
60
70
80
90
100
110
120
130
140
150
160
170
180



47 MILE PROFILE 6
850 M³/S
142 M³/S
Elevation (m)
95
93
91
89
87
85
83
81
79
77
75
Distance (m)
80
90
100
110
120
130
140
150
160
170
180
10-20-92
10-11-93

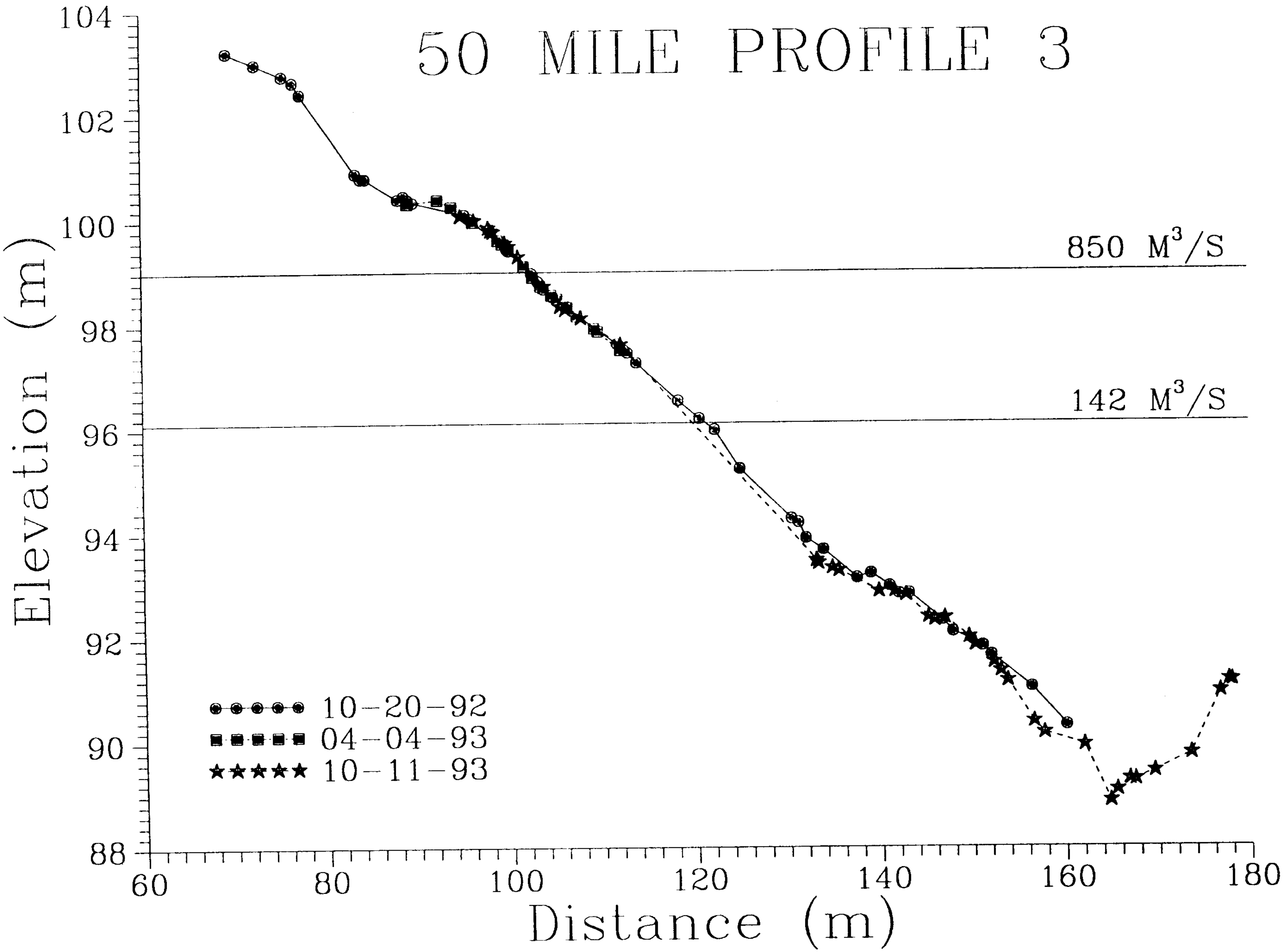

47 MILE
HAZ Volume (m3)
9500
9000
8500
8000
7500
7000
6500
6000
5500
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

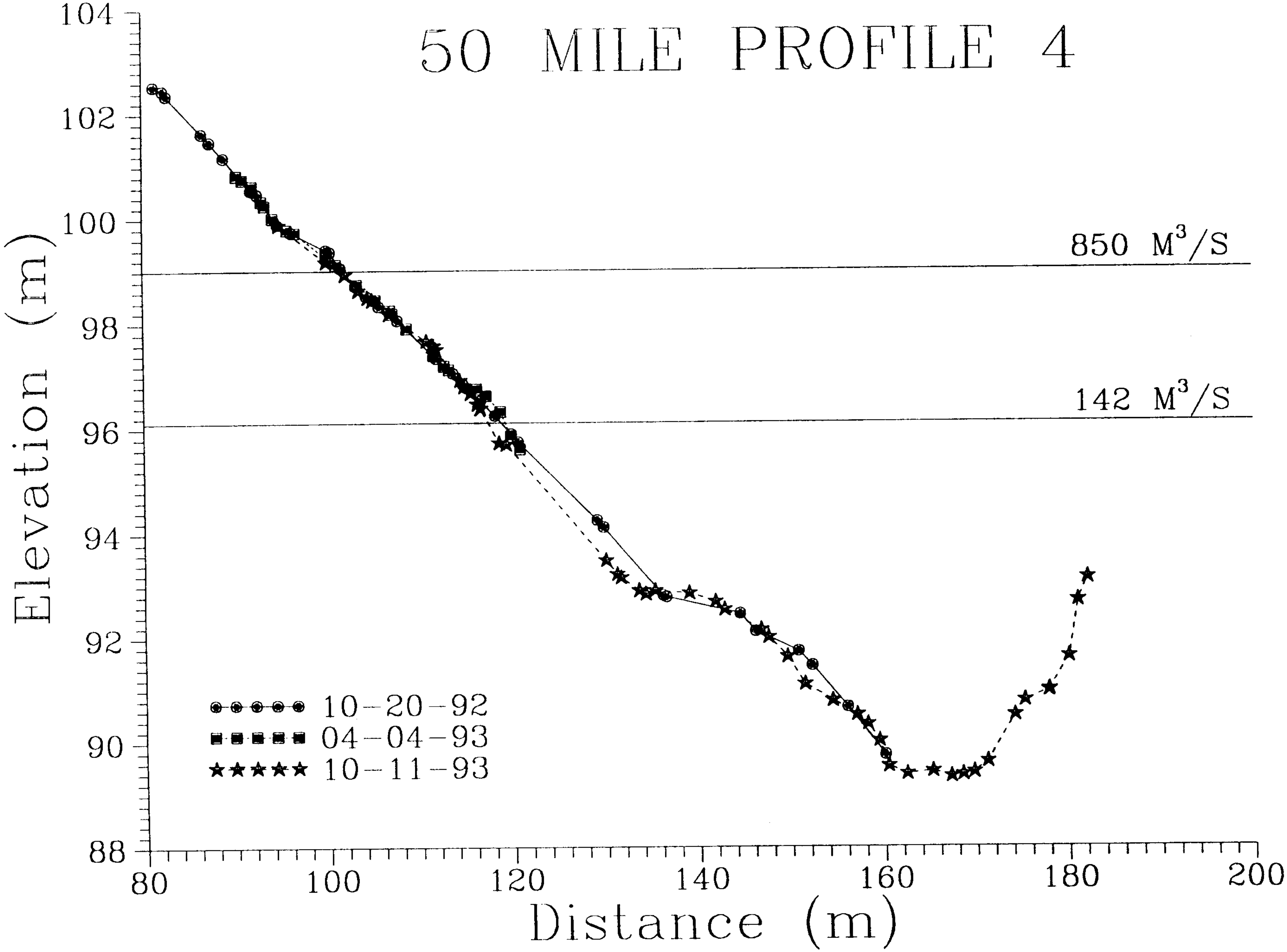

50
RM 50.0

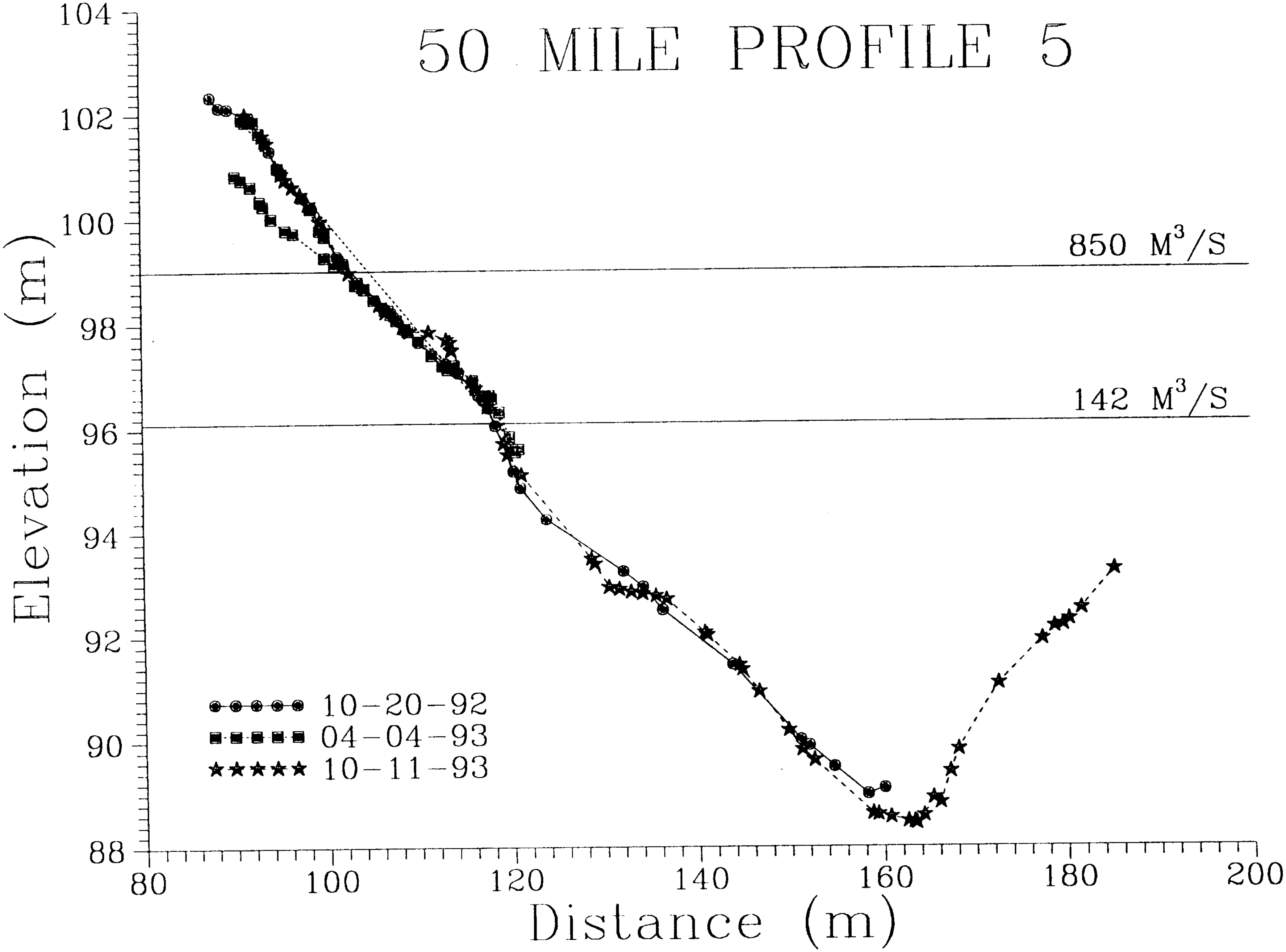


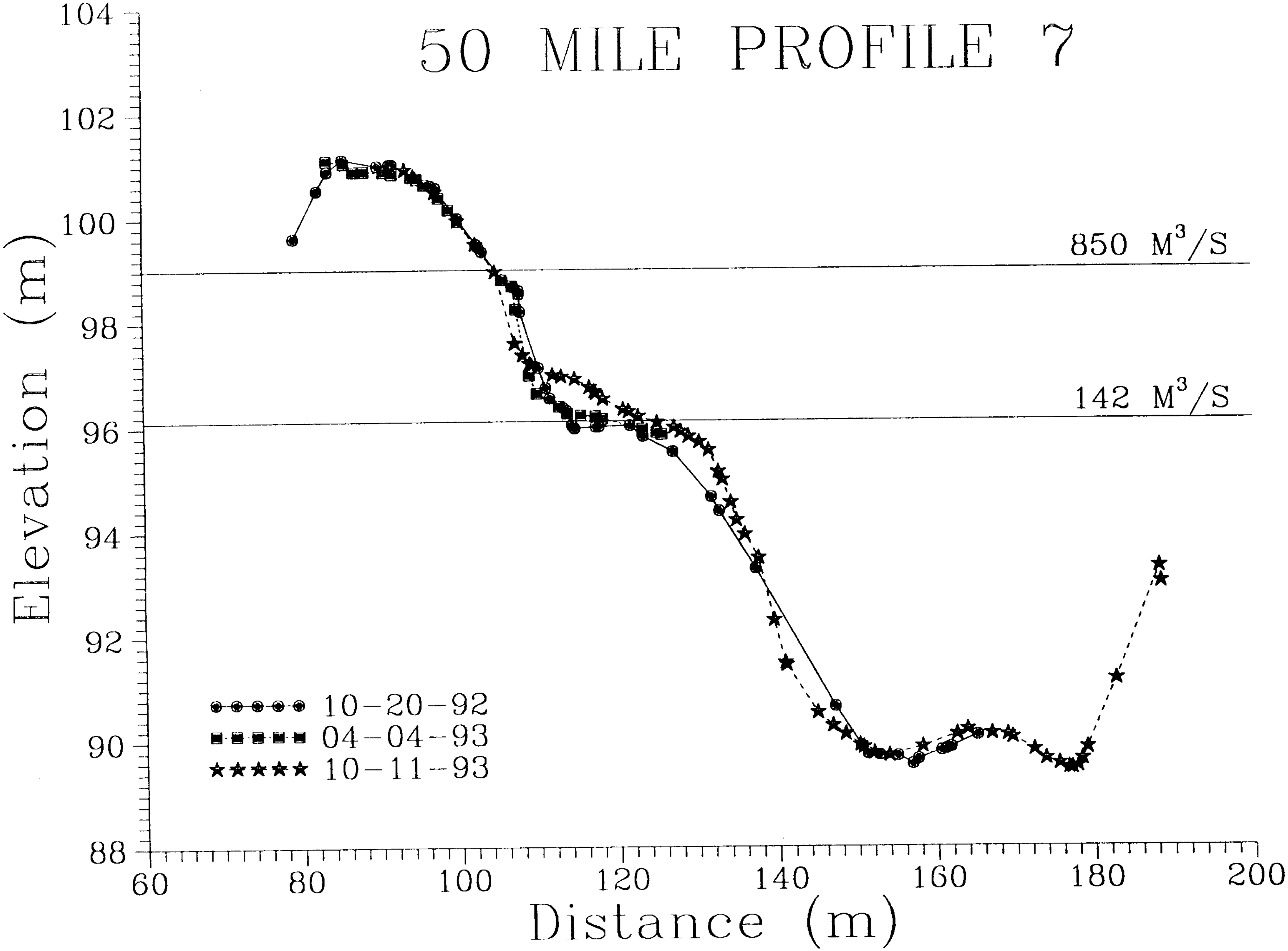
~~SLR-B13~~ 50R-B13

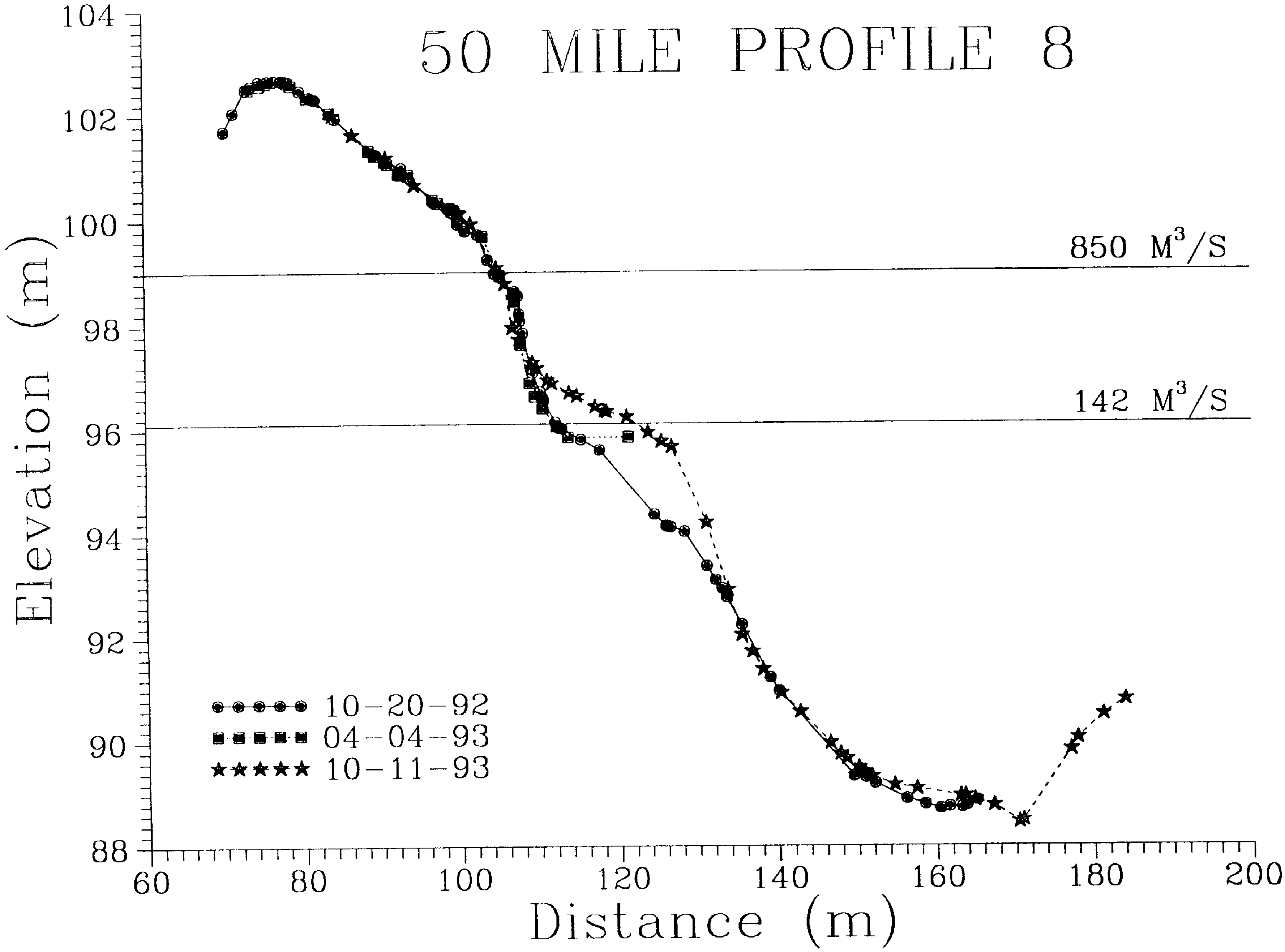
GCES BEACH SURVEY B13 10-11-93 1: 675

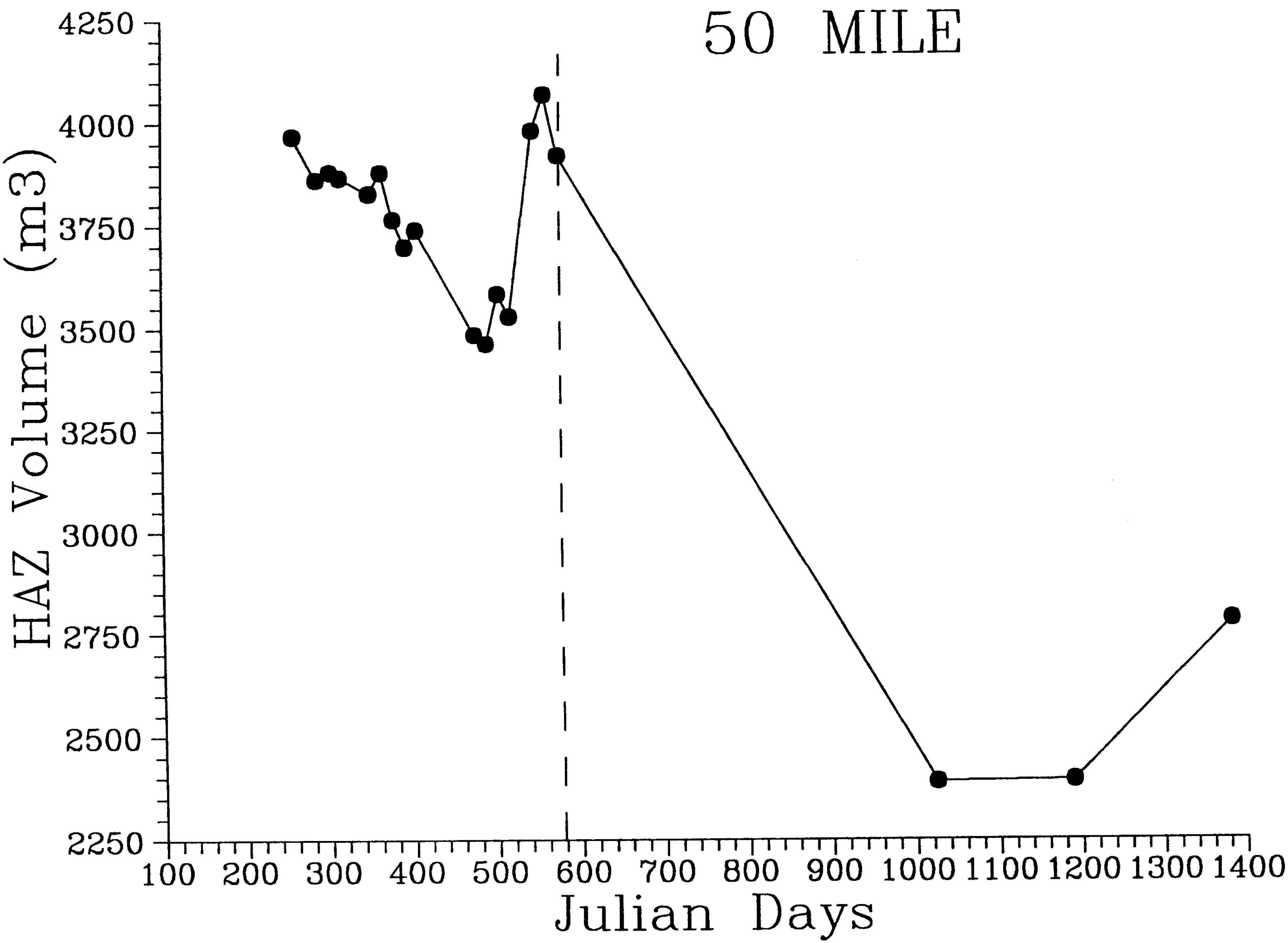

50 MILE PROFILE 3
850 M3/S
142 M3/S
10-20-92
04-04-93
10-11-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
88
60
80
100
120
140
160
180


50 MILE PROFILE 4
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
88
80
100
120
140
160
180
200
10-20-92
04-04-93
10-11-93

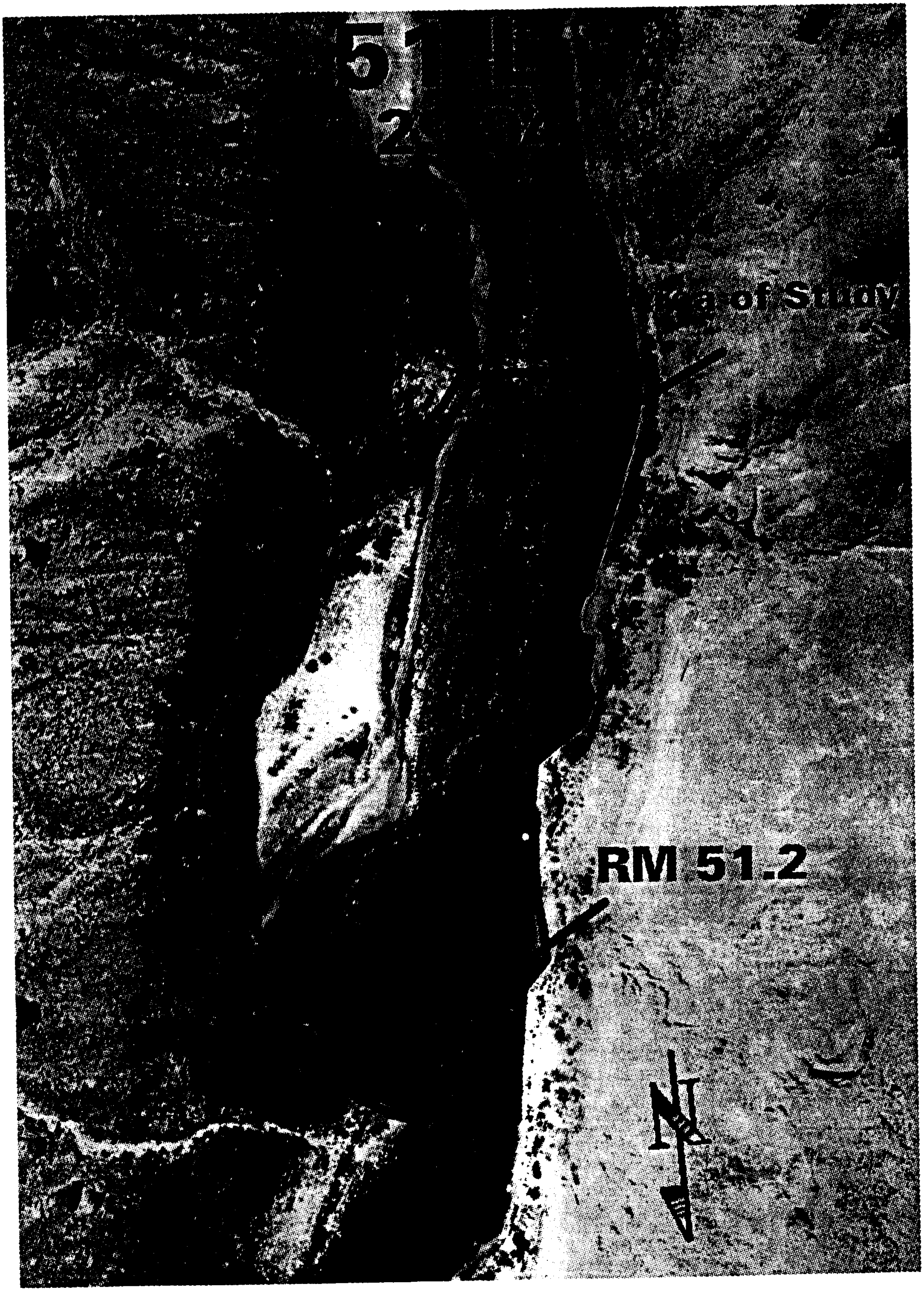

50 MILE PROFILE 5
850 M^3/S
142 M^3/S
10-20-92
04-04-93
10-11-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
88
80
100
120
140
160
180
200


50 MILE PROFILE 7
850 M^3/S
142 M^3/S
10-20-92
04-04-93
10-11-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
88
60
80
100
120
140
160
180
200

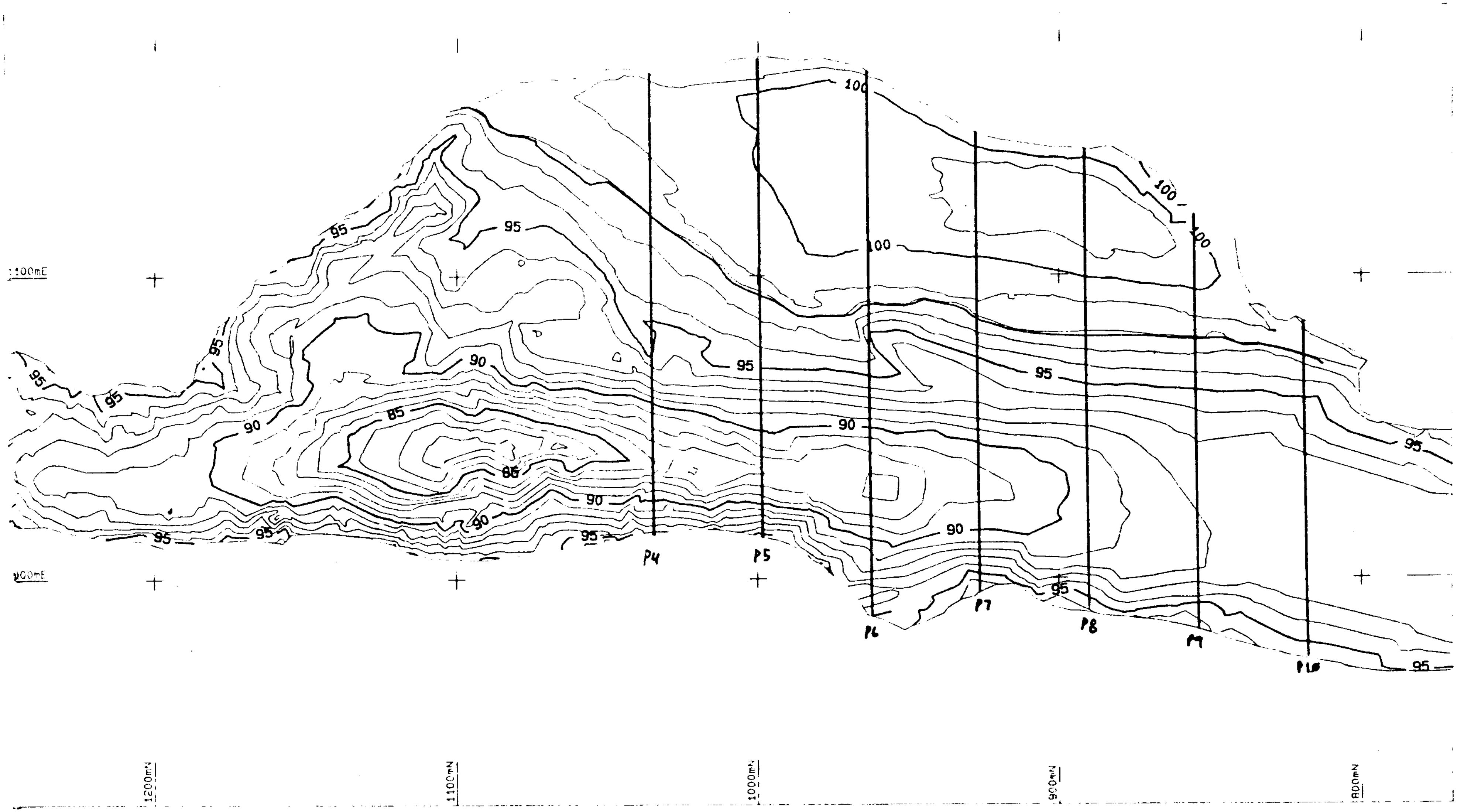

50 MILE PROFILE 8
850 M³/S
142 M³/S
10-20-92
04-04-93
10-11-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
88
60
80
100
120
140
160
180
200



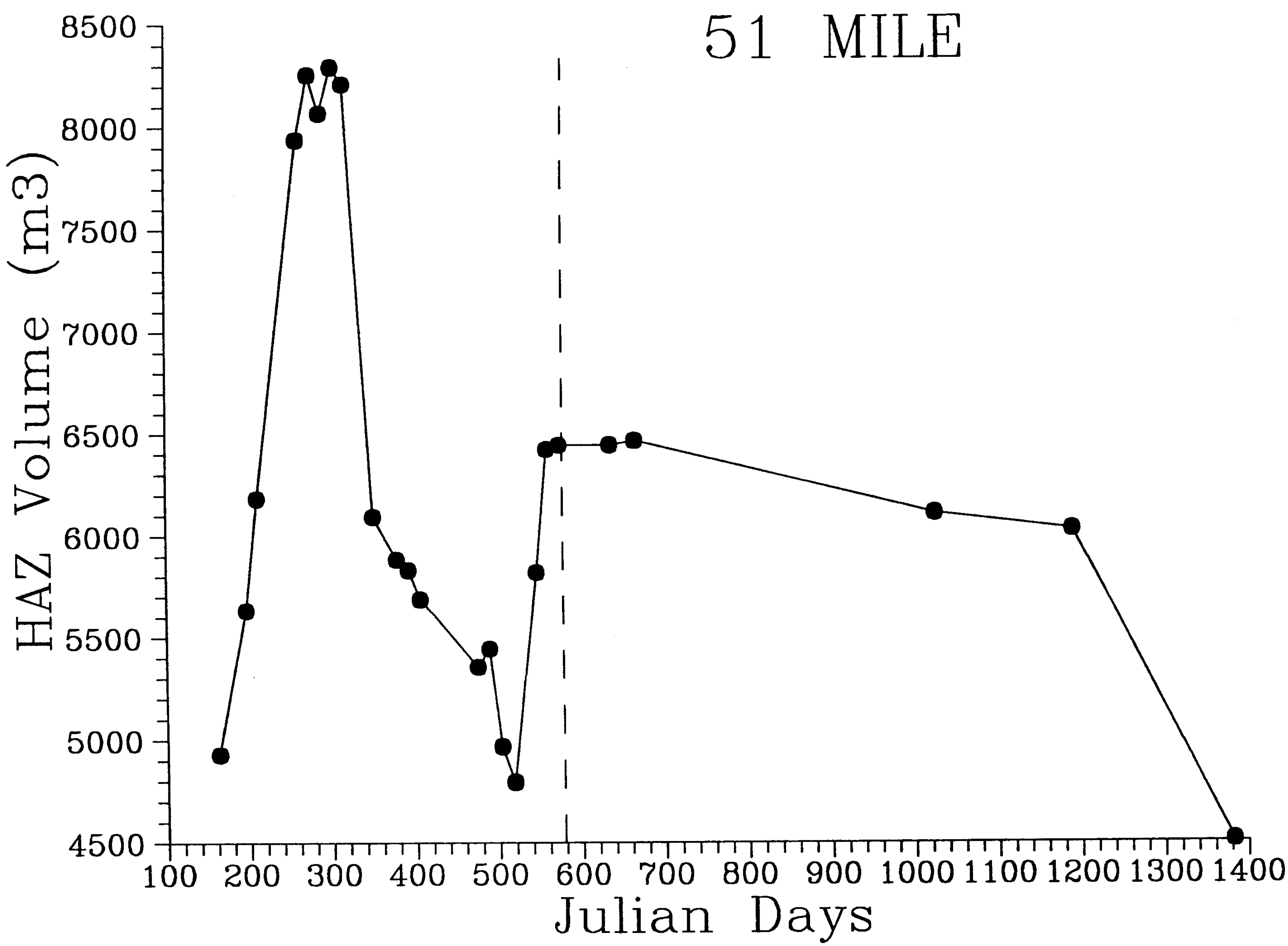
50 MILE
HAZ Volume (m3)
4250
4000
3750
3500
3250
3000
2750
2500
2250
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

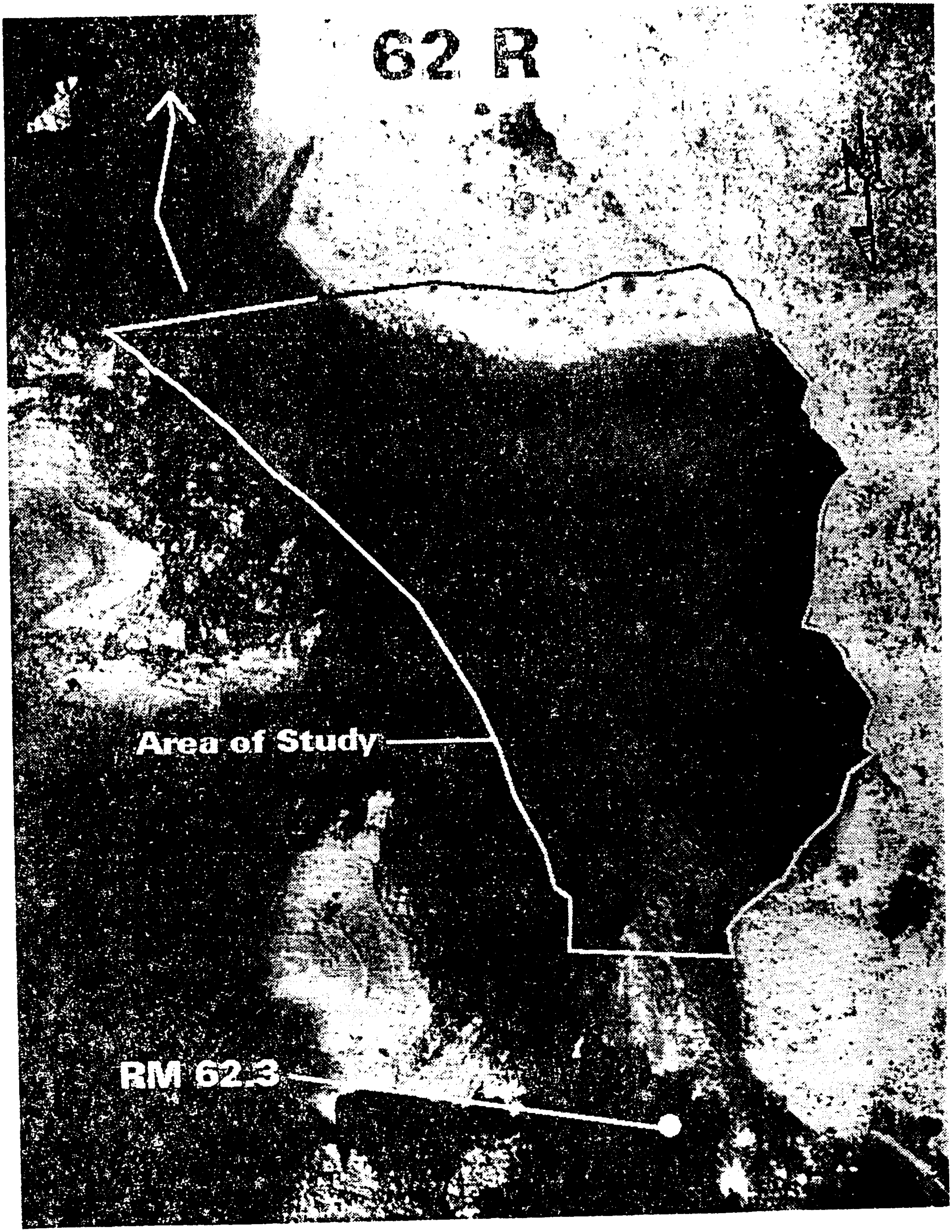


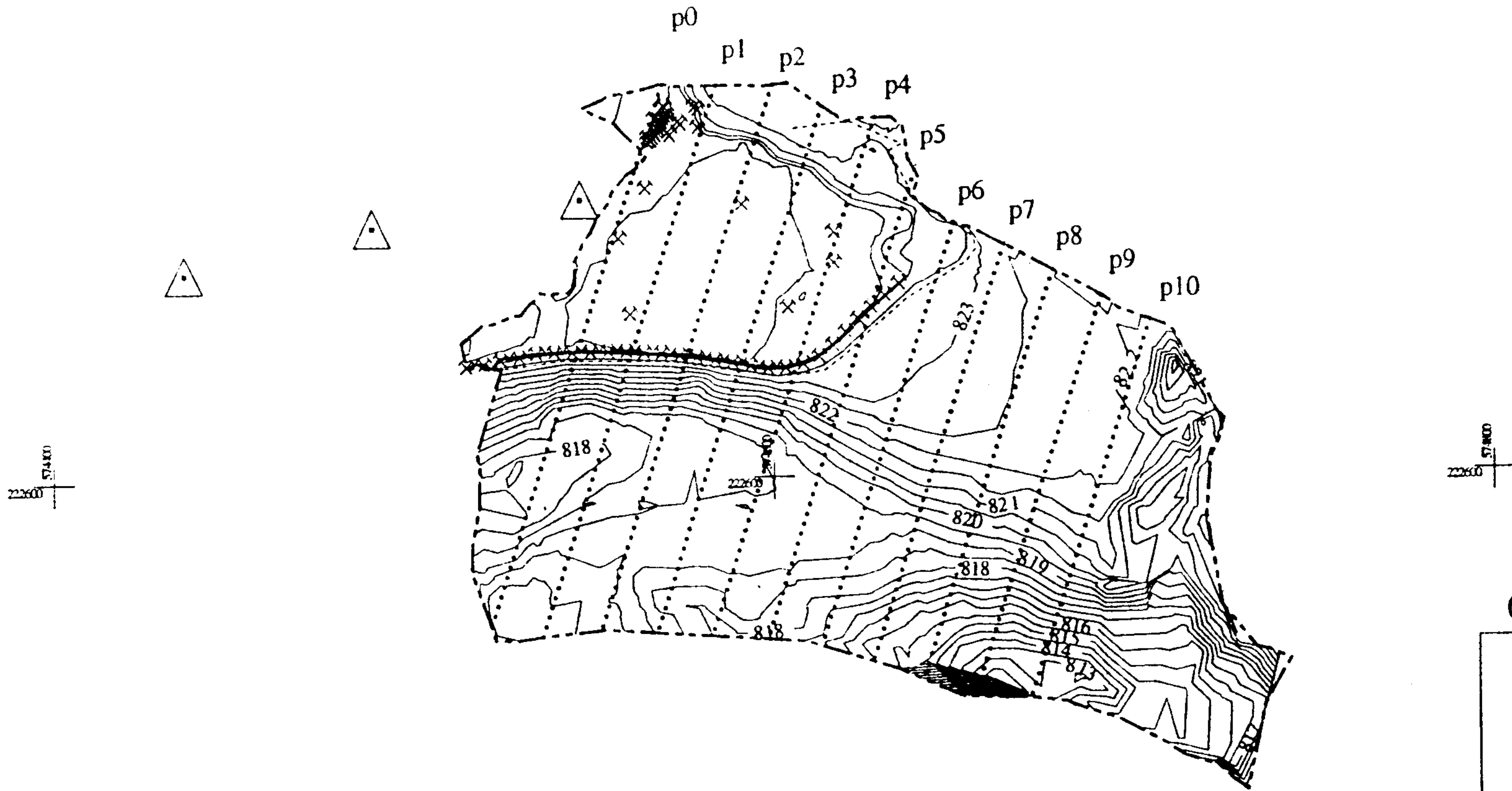
RM 51.2
N



GCES BEACH SURVEY B14 51L-B14 BYTH 10-12-93 1: 1200


51 MILE
HAZ Volume (m3)
8500
8000
7500
7000
6500
6000
5500
5000
4500
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days


62 R
Area of Study
RM 62.3



62R – Crash Canyon

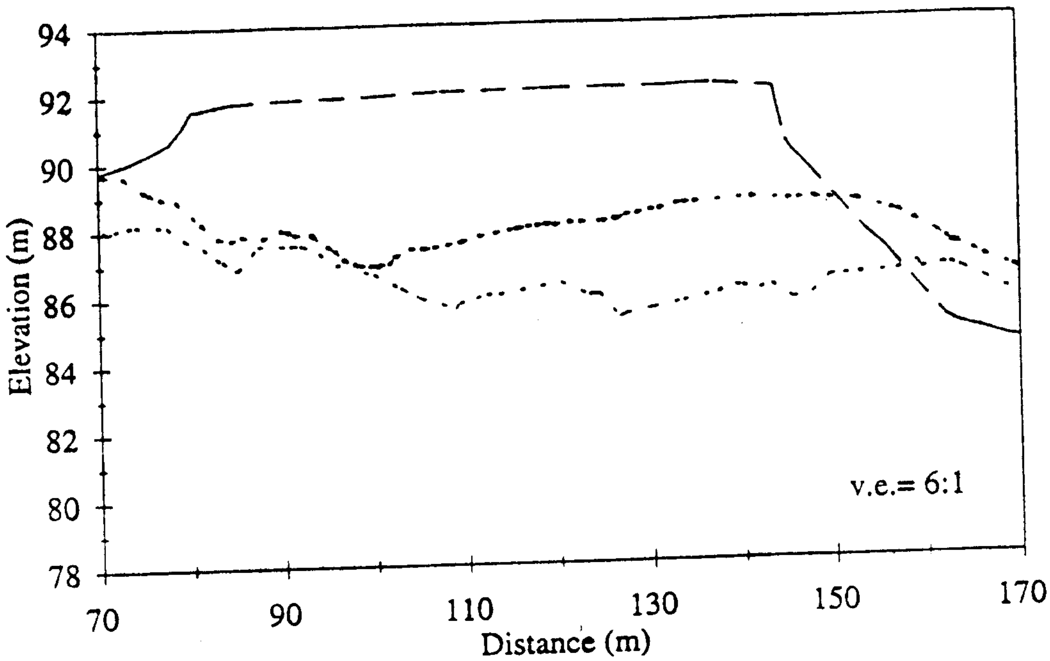
0.5 Meter Contour Interval
Survey_Date:_4/13/94
AZ State Plane Coordinates
Elevations in Meters above Sea Level

- Camera Locations
- Survey Control Points
- Sediment/Stratigraphy Sample Locations
- Profile Lines
- Water Line

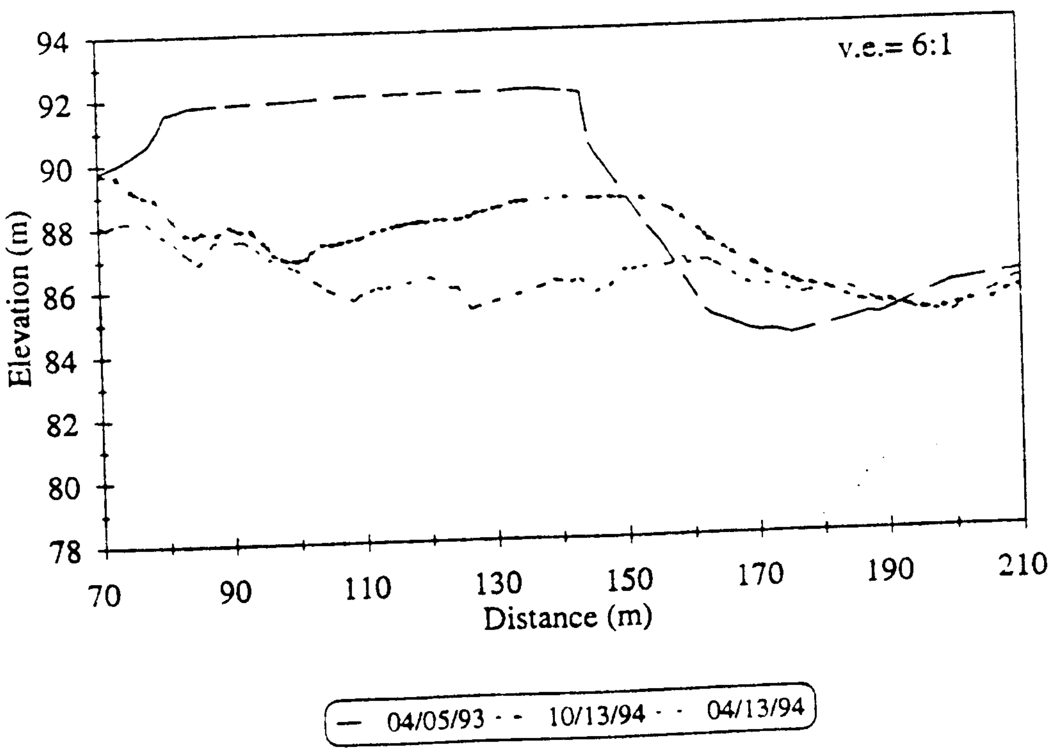
Scale 1:1500

62 Mile

Near-shore P1

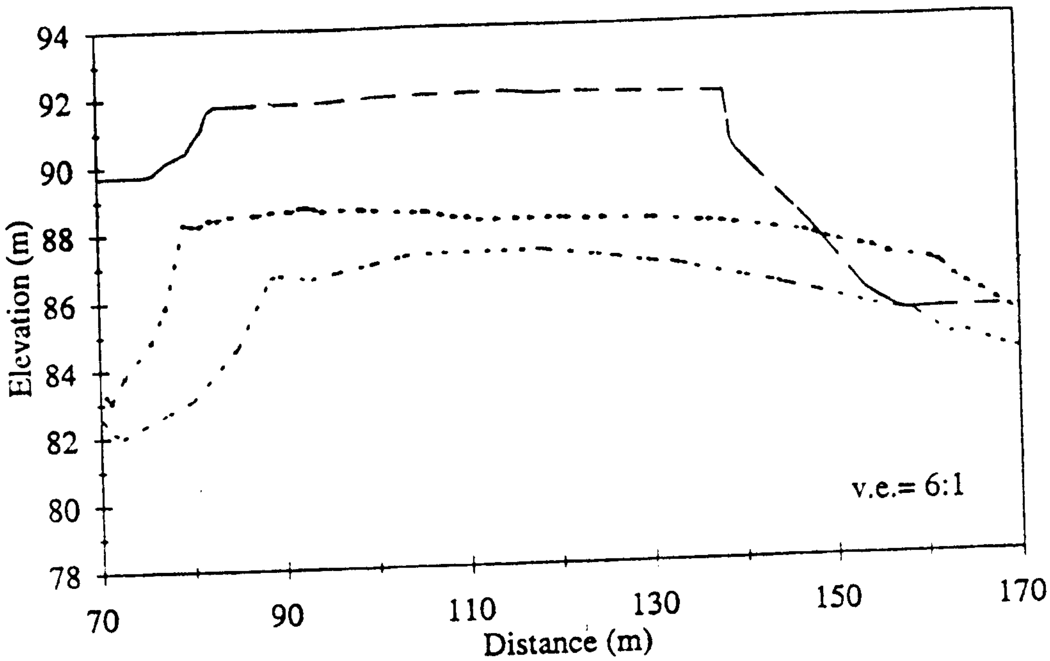


Cross-channel P1

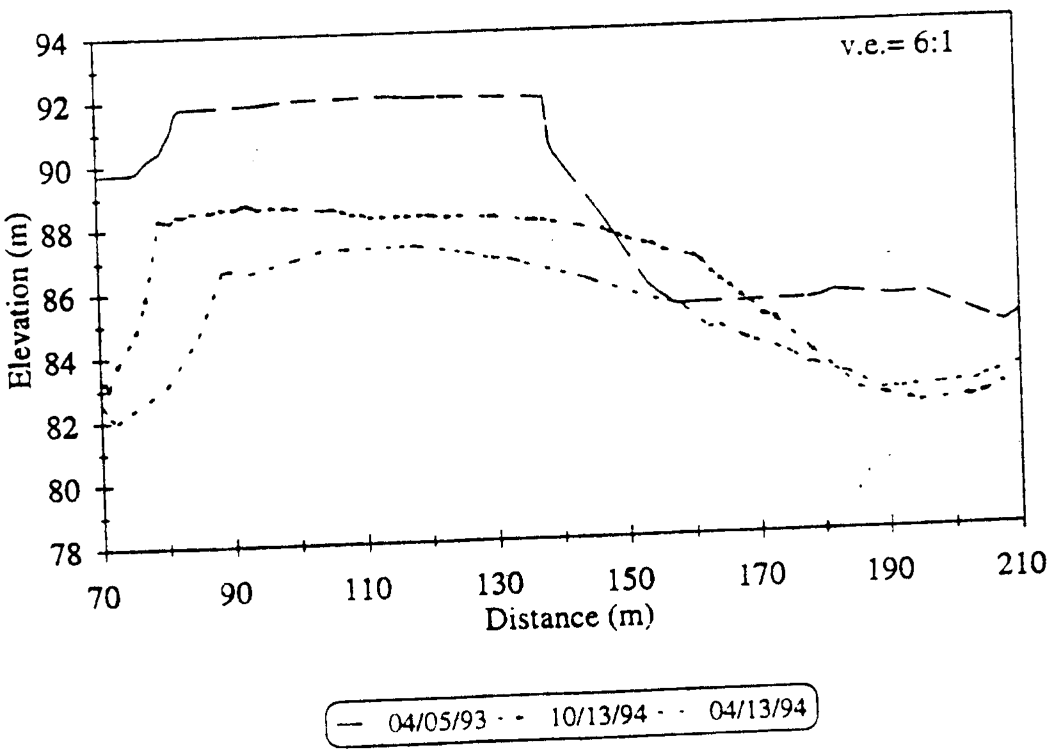


62 Mile

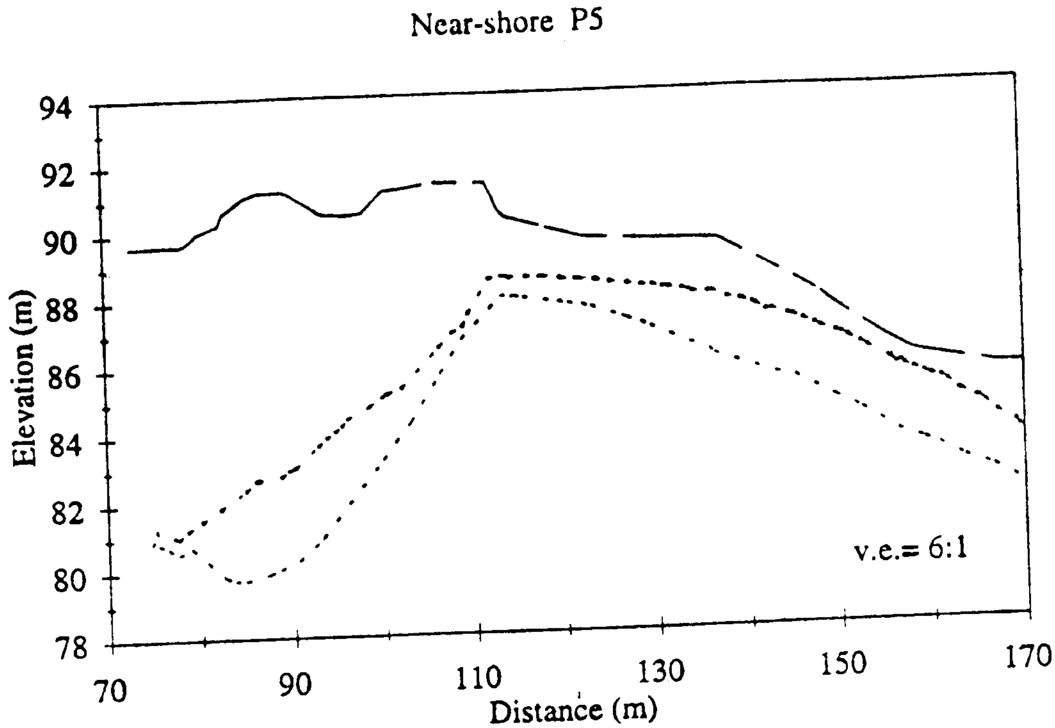
Near-shore P3

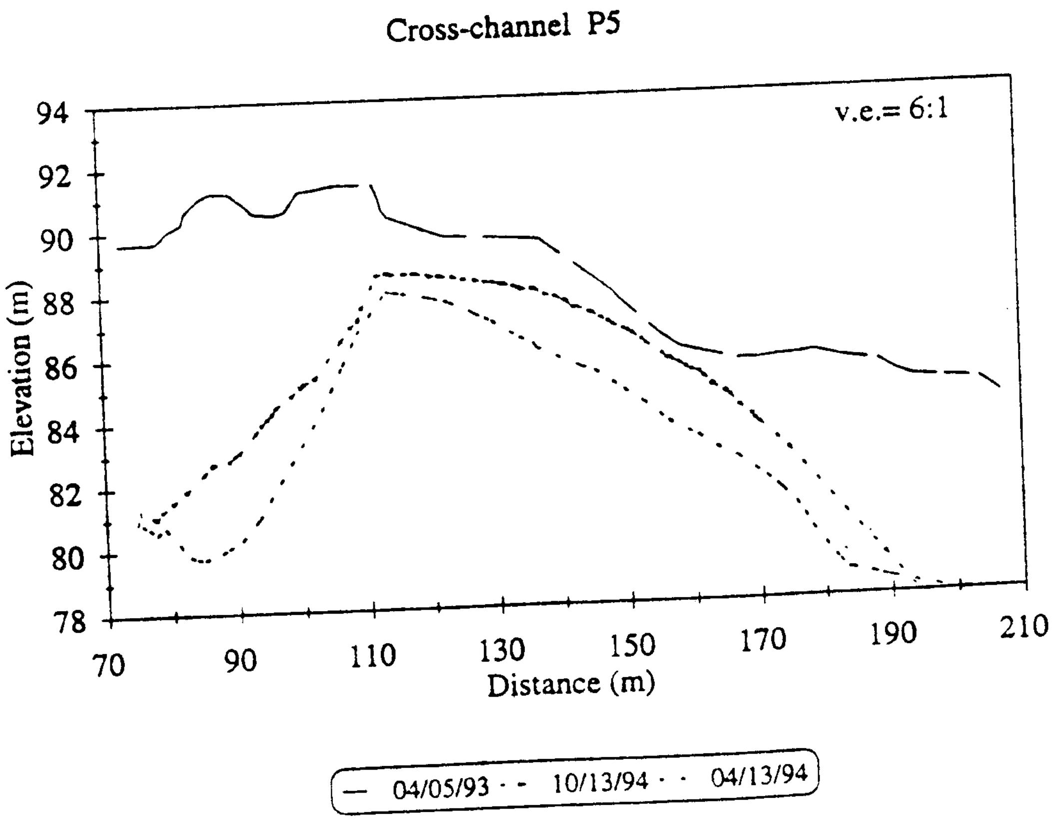


Cross-channel P3

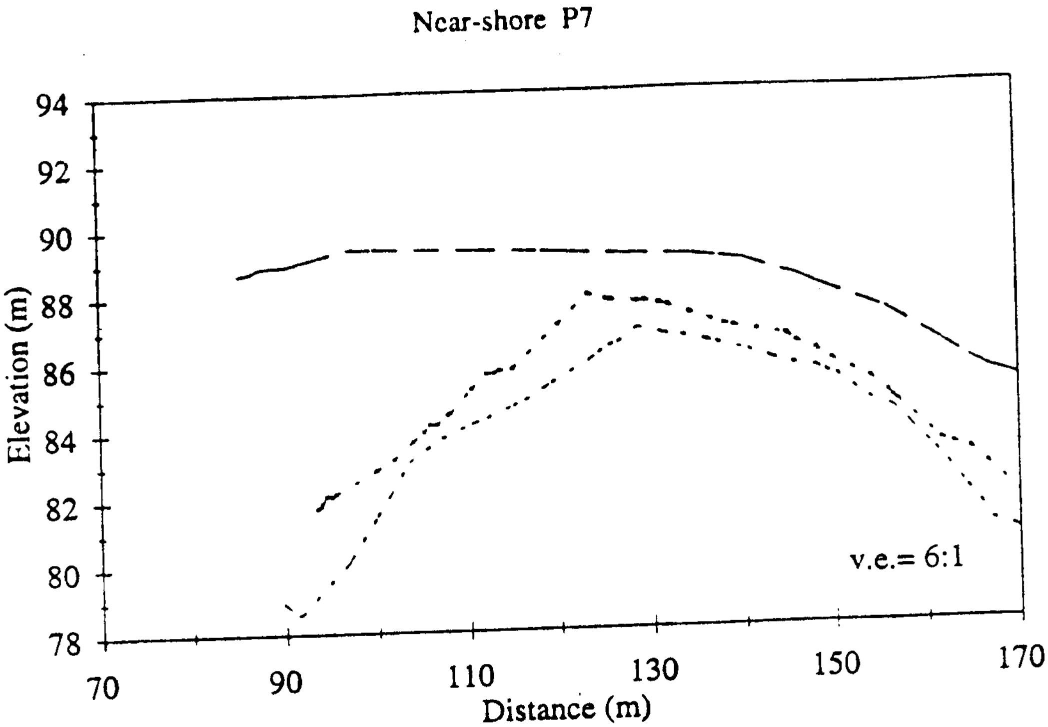


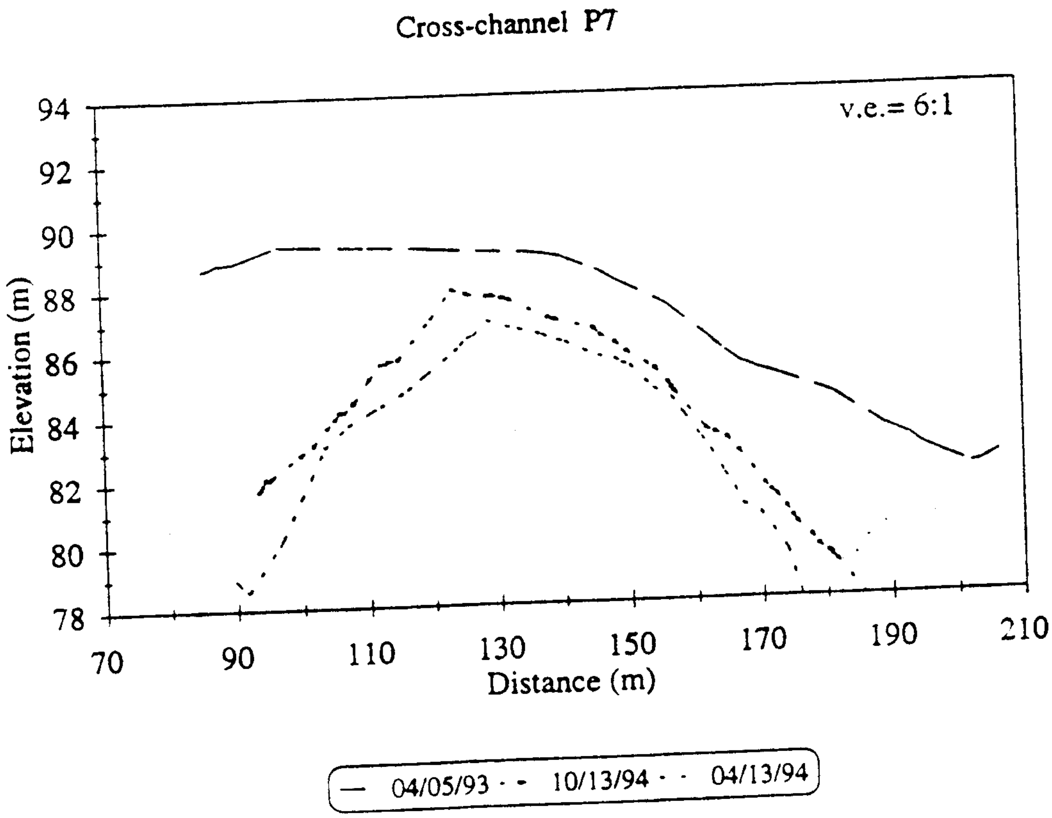
62 Mile

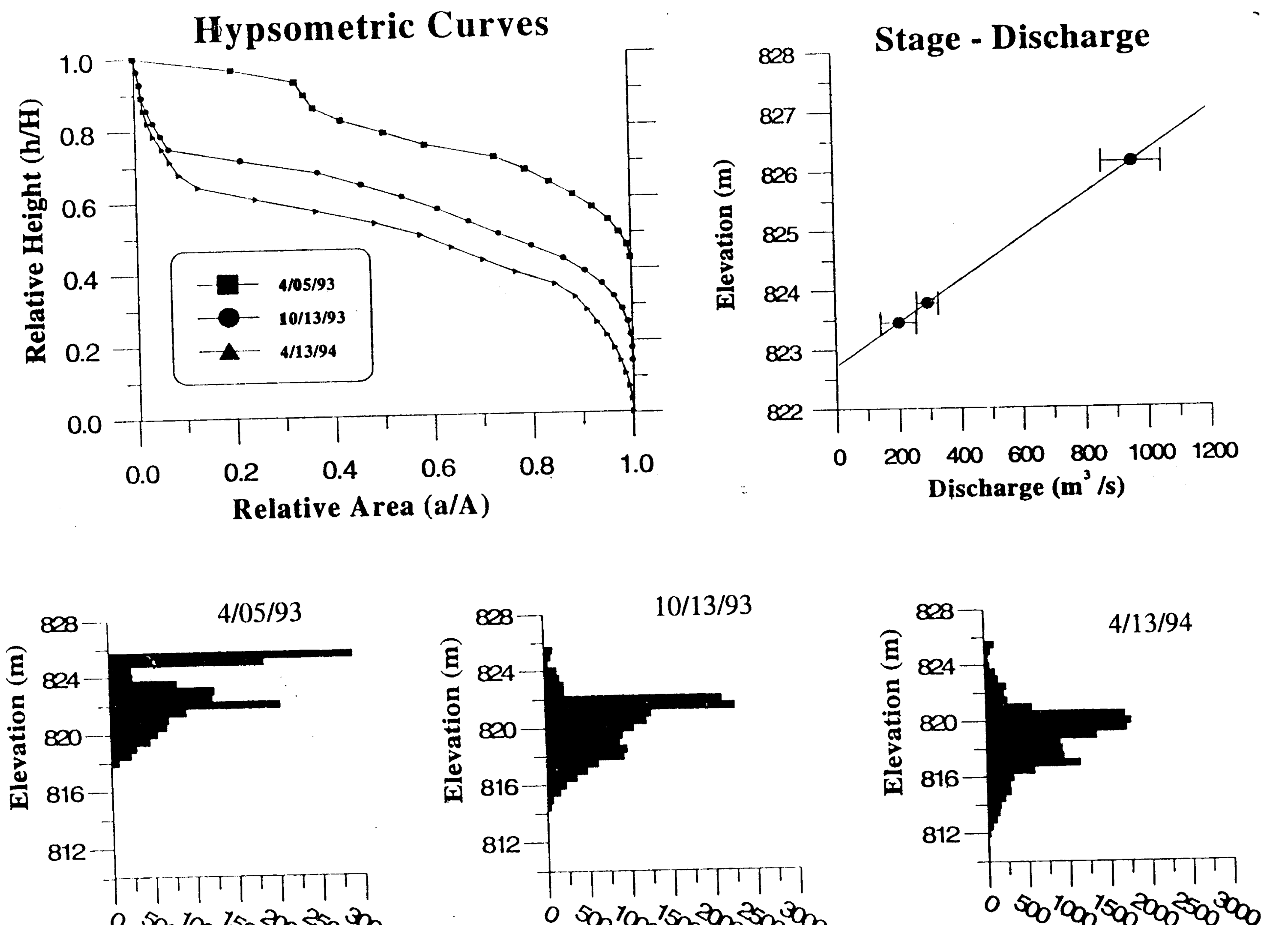

Near-shore P5
94
92
90
88
86
84
82
80
78
Elevation (m)
v.e.= 6:1
70
90
110
130
150
170
Distance (m)

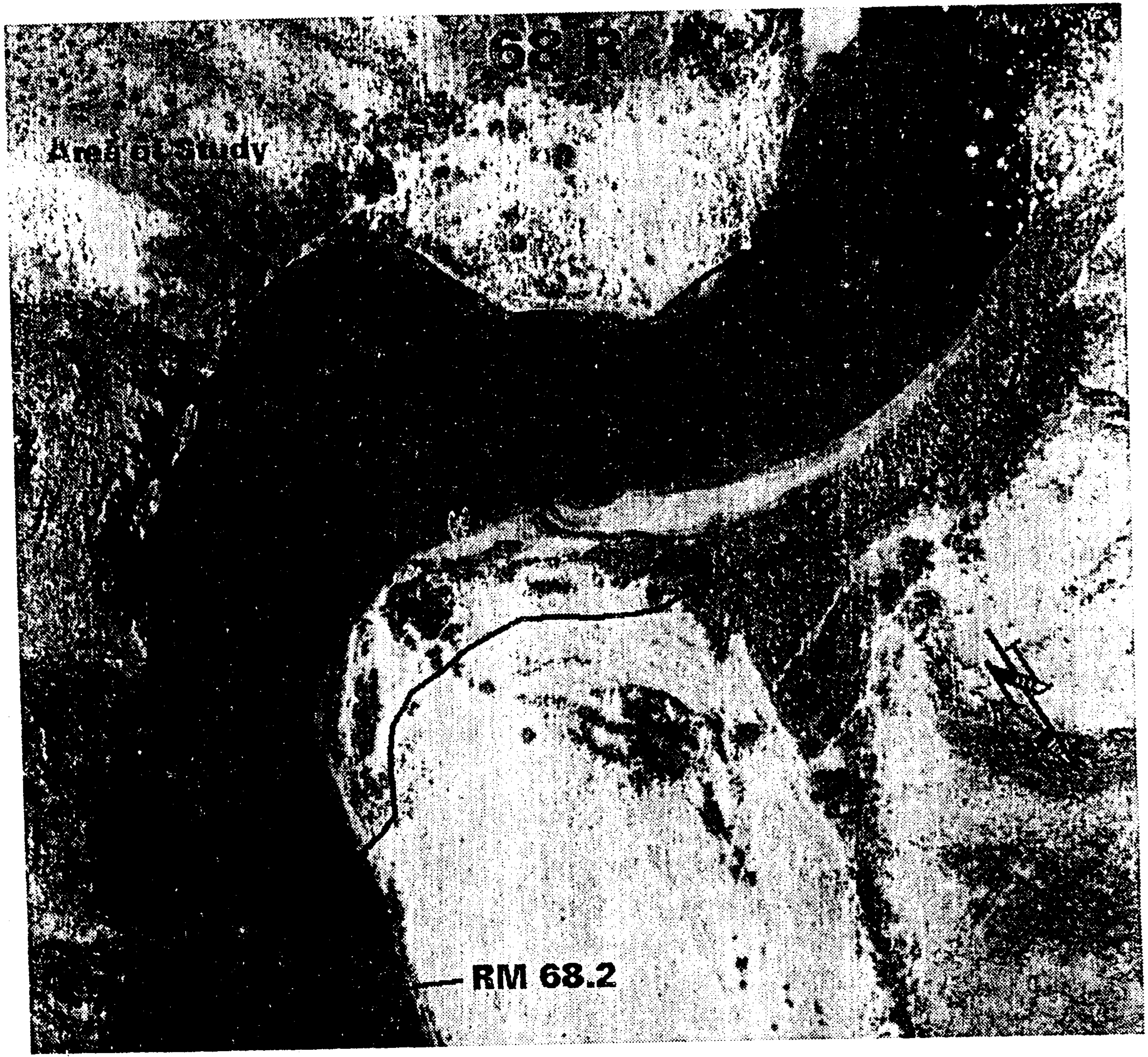

Cross-channel P5
94
92
90
88
86
84
82
80
78
Elevation (m)
v.e.= 6:1
70
90
110
130
150
170
190
210
Distance (m)
04/05/93
10/13/94
04/13/94

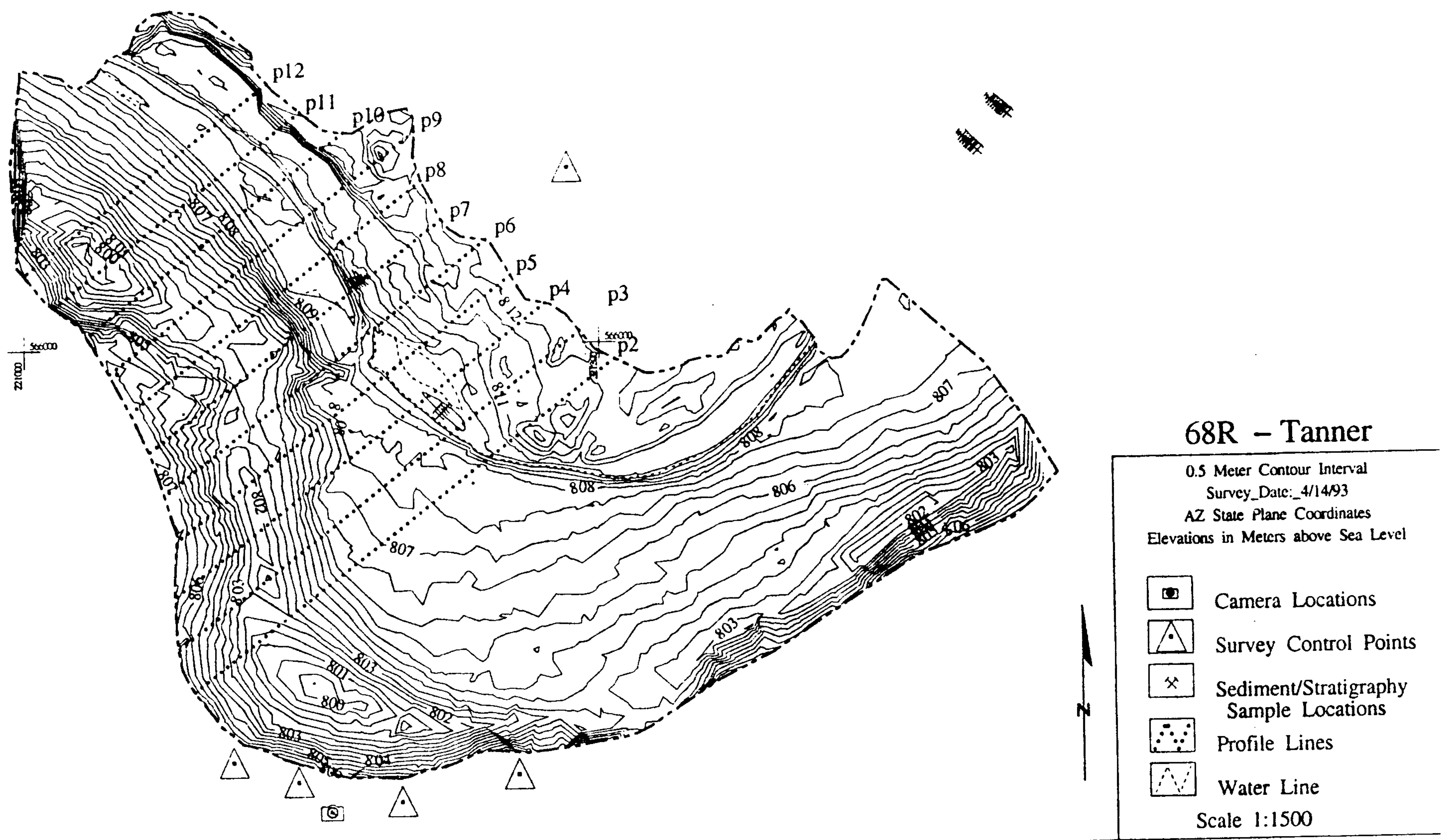
62 Mile


Near-shore P7
94
92
90
88
86
84
82
80
78
Elevation (m)
70
90
110
130
150
170
Distance (m)
v.e.= 6:1


Cross-channel P7
v.e.= 6:1
94
92
90
88
86
84
82
80
78
Elevation (m)
70
90
110
130
150
170
190
210
Distance (m)
04/05/93
10/13/94
04/13/94


Hypsometric Curves
Relative Height (h/H)
Relative Area (a/A)
4/05/93
10/13/93
4/13/94
1.0
0.8
0.6
0.4
0.2
0.0
Stage - Discharge
Elevation (m)
Discharge (m³/s)
828
827
826
825
824
823
822
0
200
400
600
800
1000
1200
4/05/93
10/13/93
4/13/94
Elevation (m)
812
816
820
824
828
0
500
1000
1500
2000
2500
3000

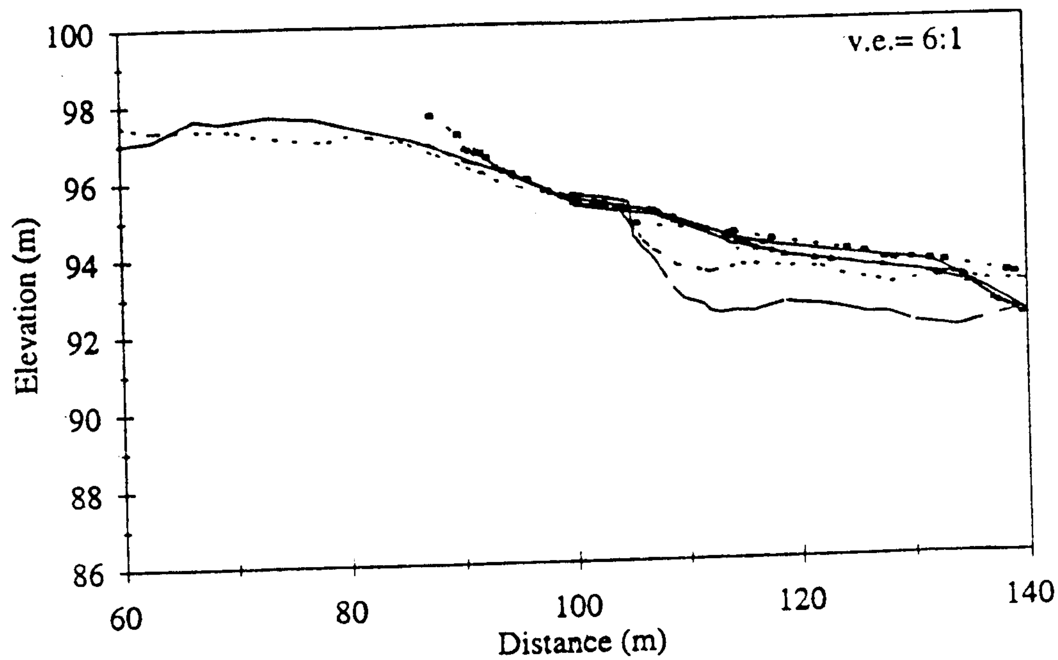

68 R
Area of Study
RM 68.2



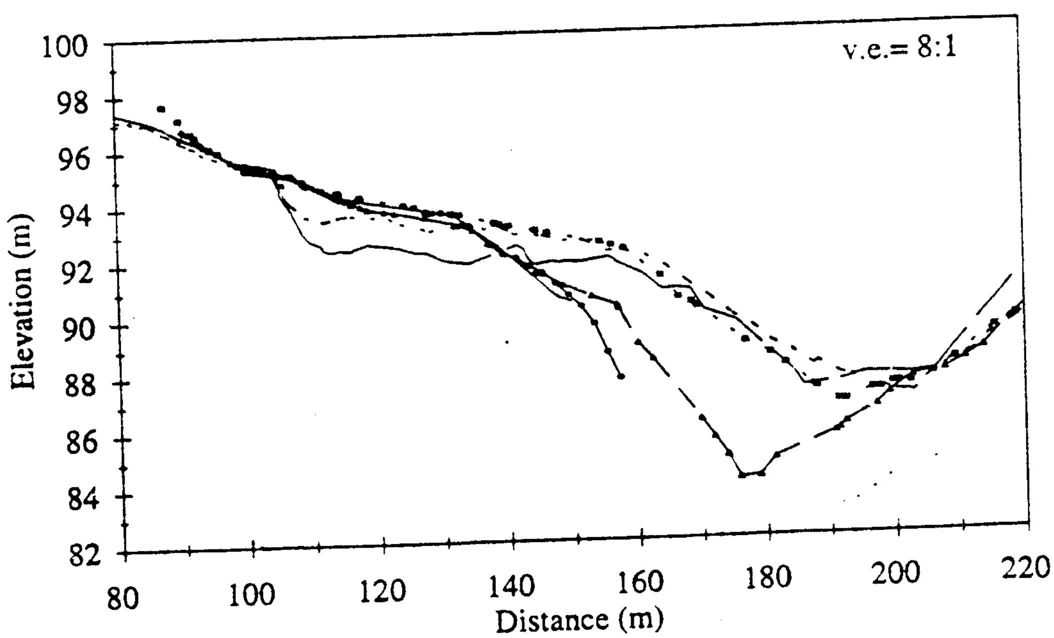
68R – Tanner
0.5 Meter Contour Interval
Survey_Date:_4/14/93
AZ State Plane Coordinates
Elevations in Meters above Sea Level
Camera Locations
Survey Control Points
Sediment/Stratigraphy Sample Locations
Profile Lines
Water Line
Scale 1:1500
N
p2
p3
p4
p5
p6
p7
p8
p9
p10
p11
p12
800
801
802
803
806
807
808
809
811
566000
221000

[illegible] Mile

Near-shore P2



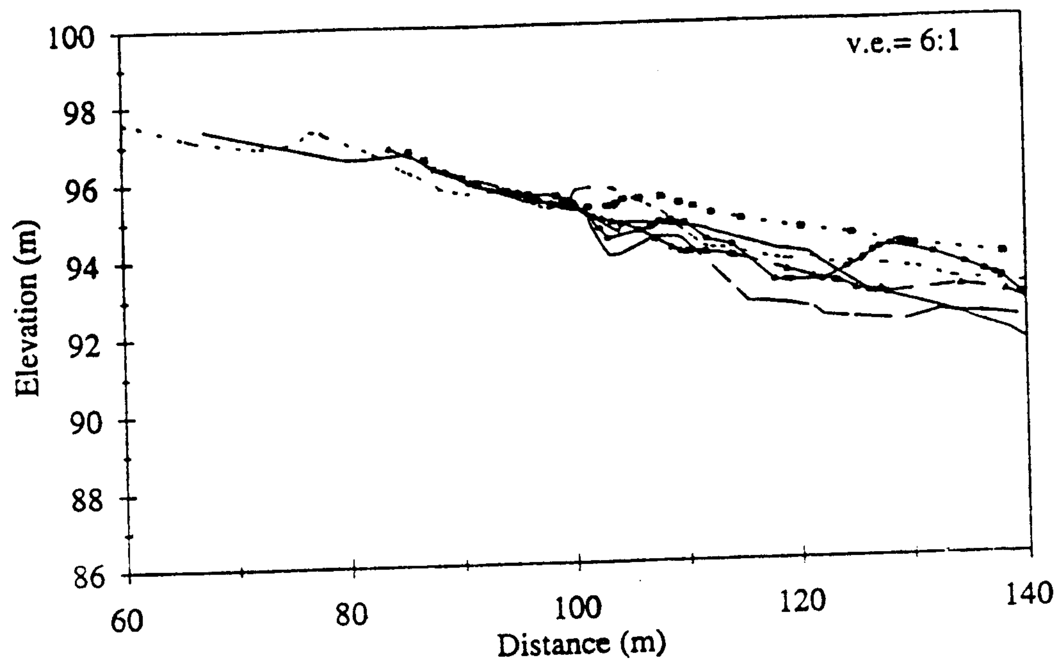
Cross-channel P2



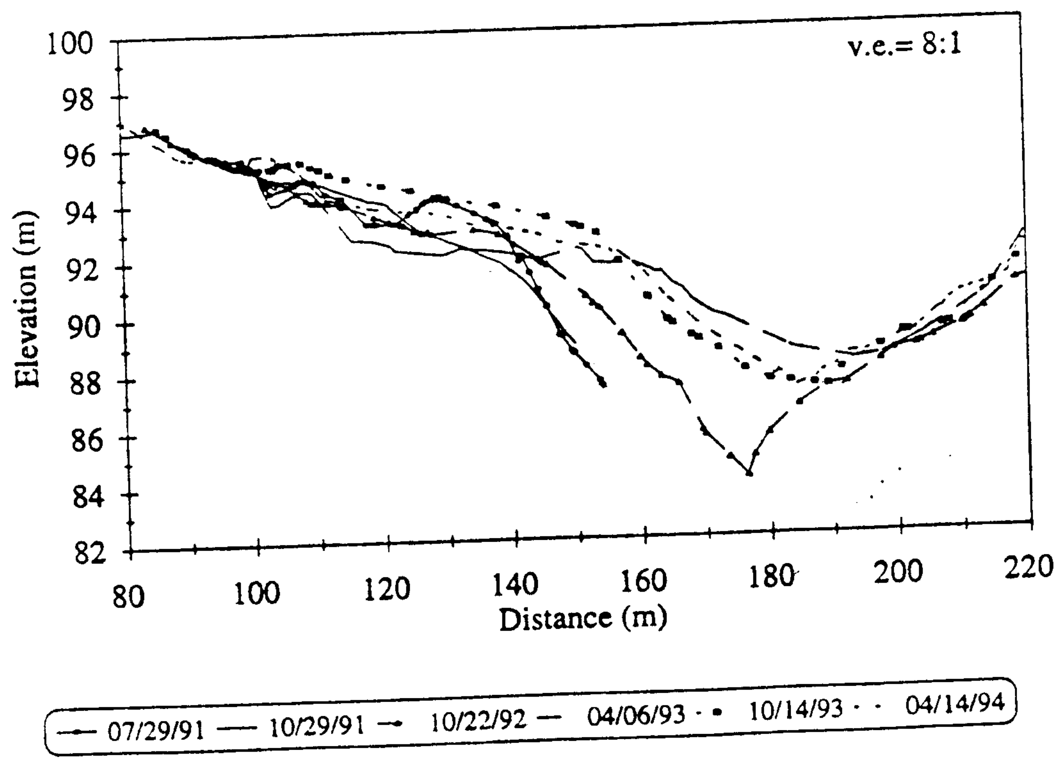
07/29/91 — 10/29/91 — 10/22/92 — 04/06/93 — 10/14/93 — 04/14/94

60 Mile

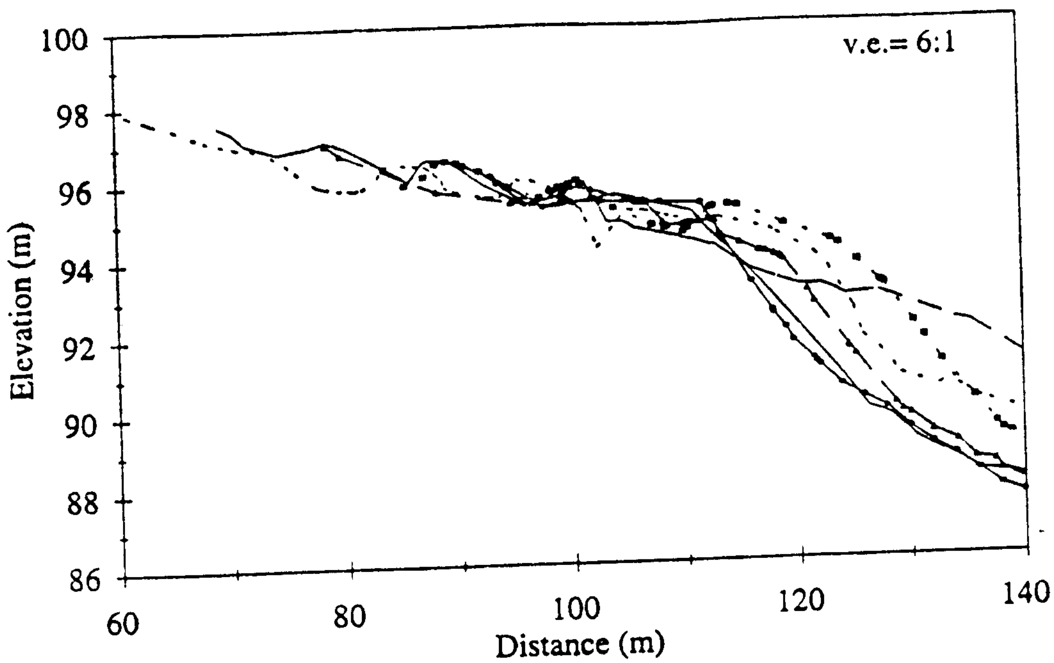
Near-shore P3



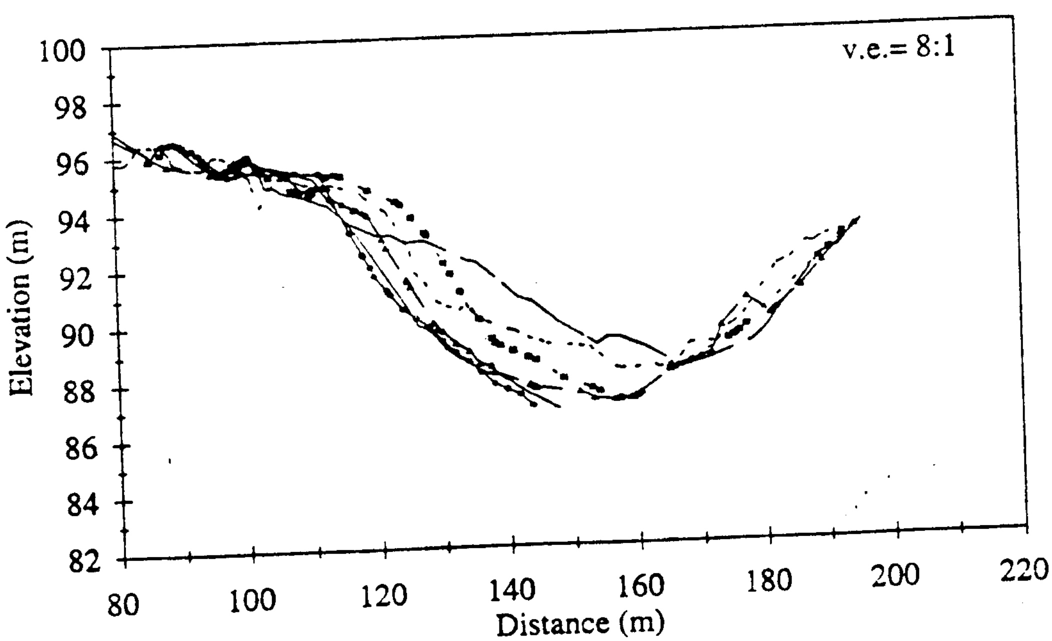
Cross-channel P3



Near-shore P6

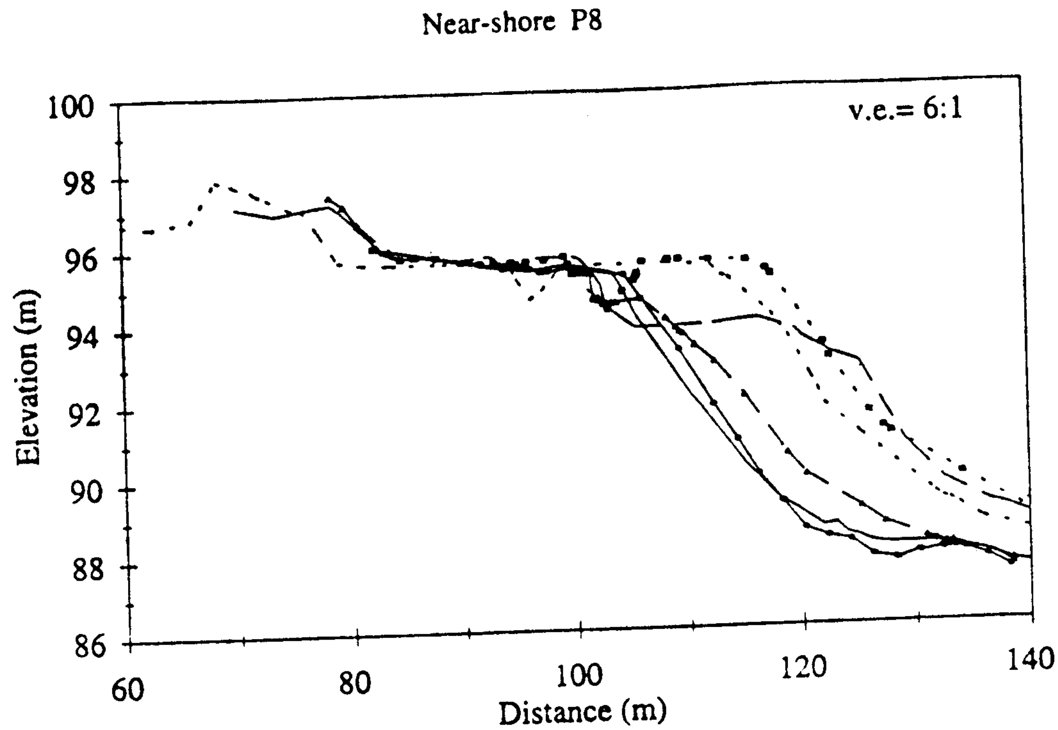


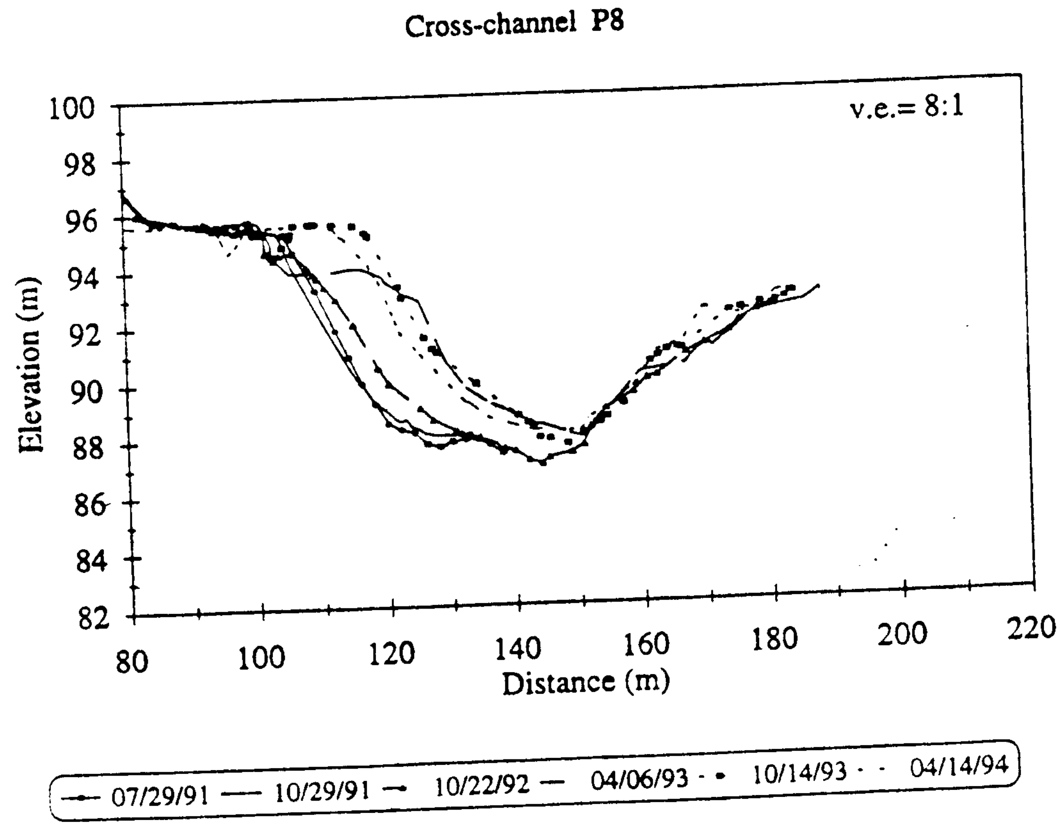
Cross-channel P6

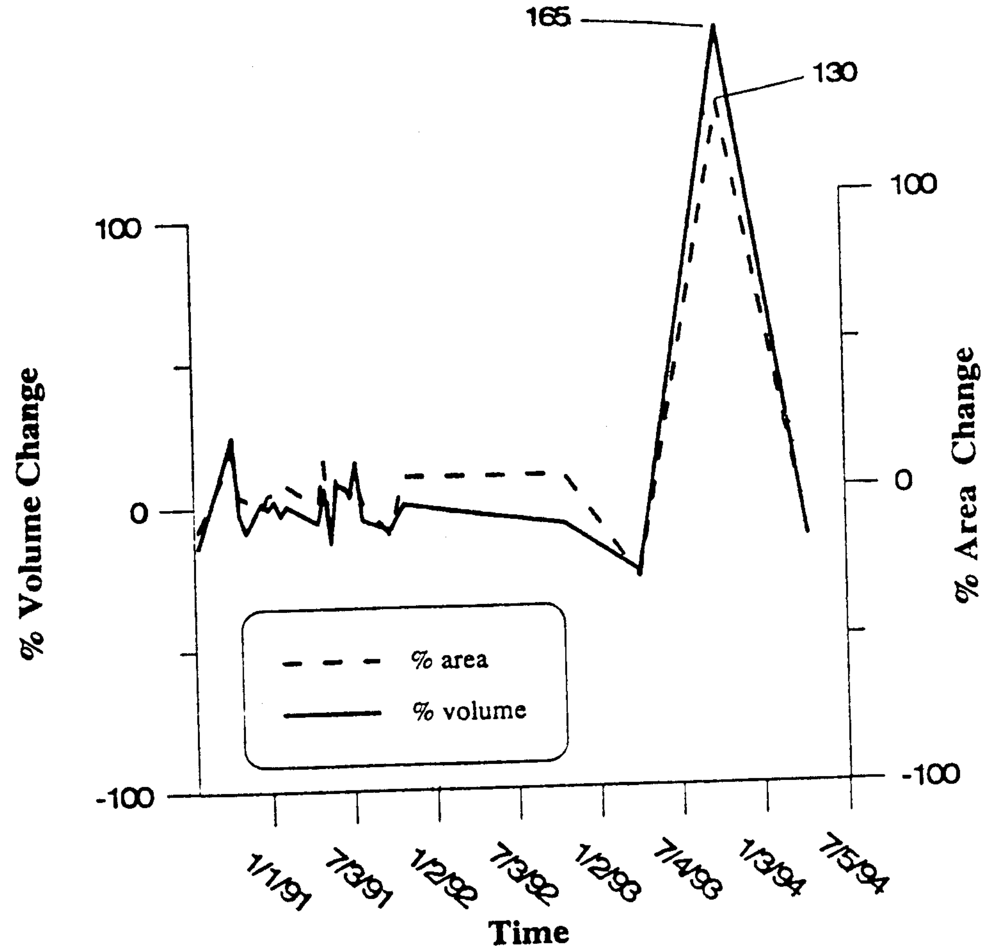


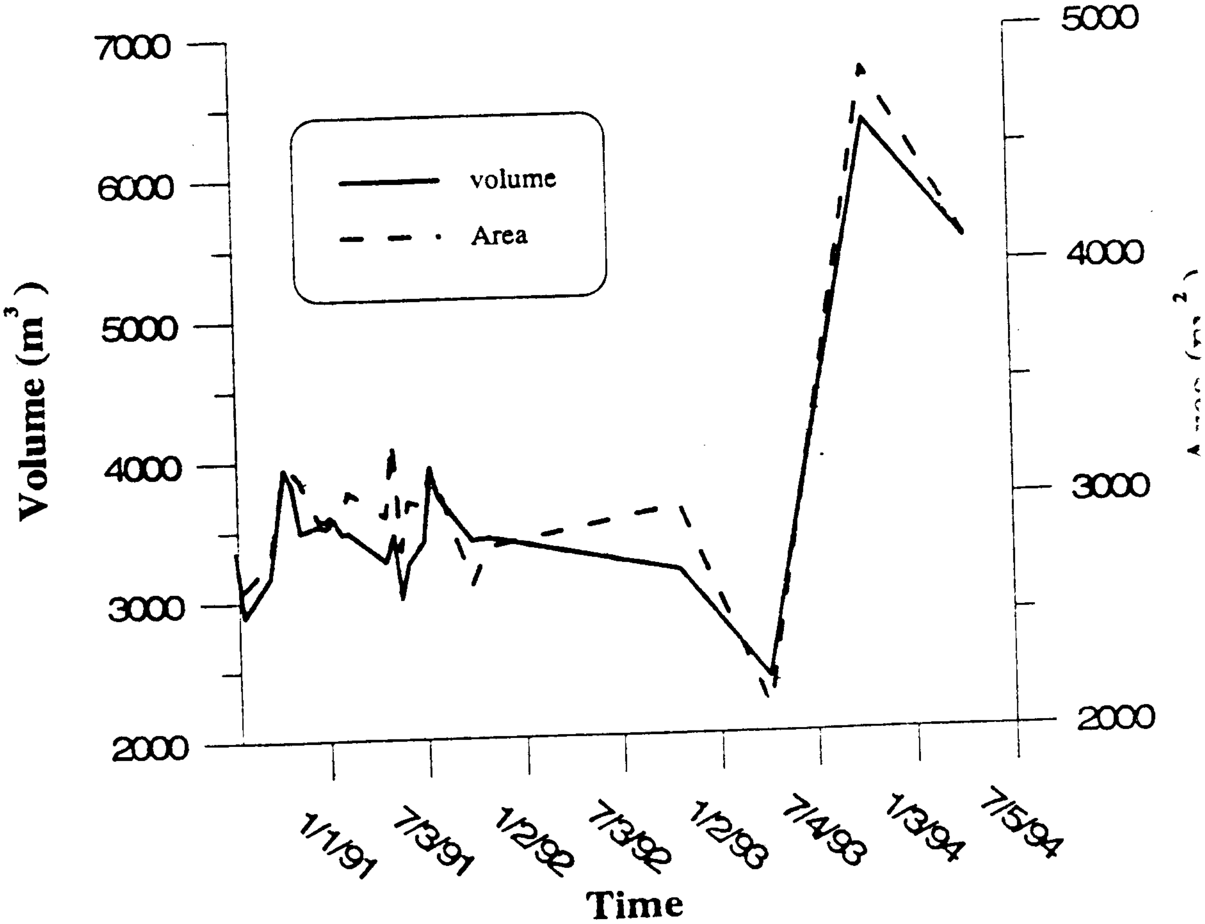
07/29/91 — 10/29/91 — 10/22/92 — 04/06/93 — 10/14/93 — 04/14/94

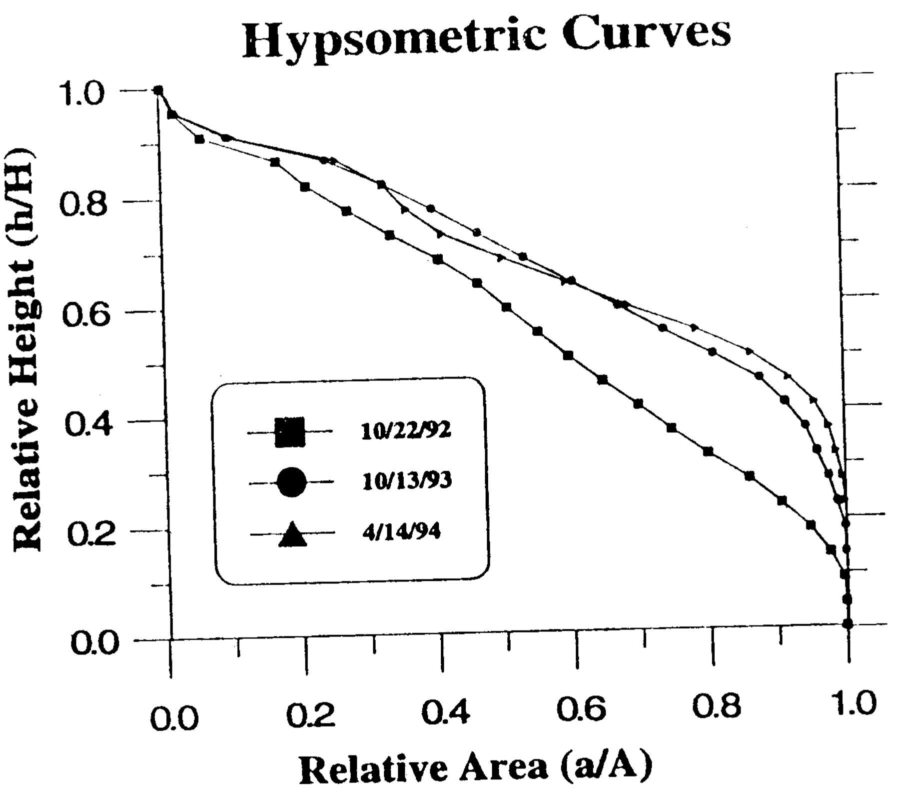
[illegible] Mile

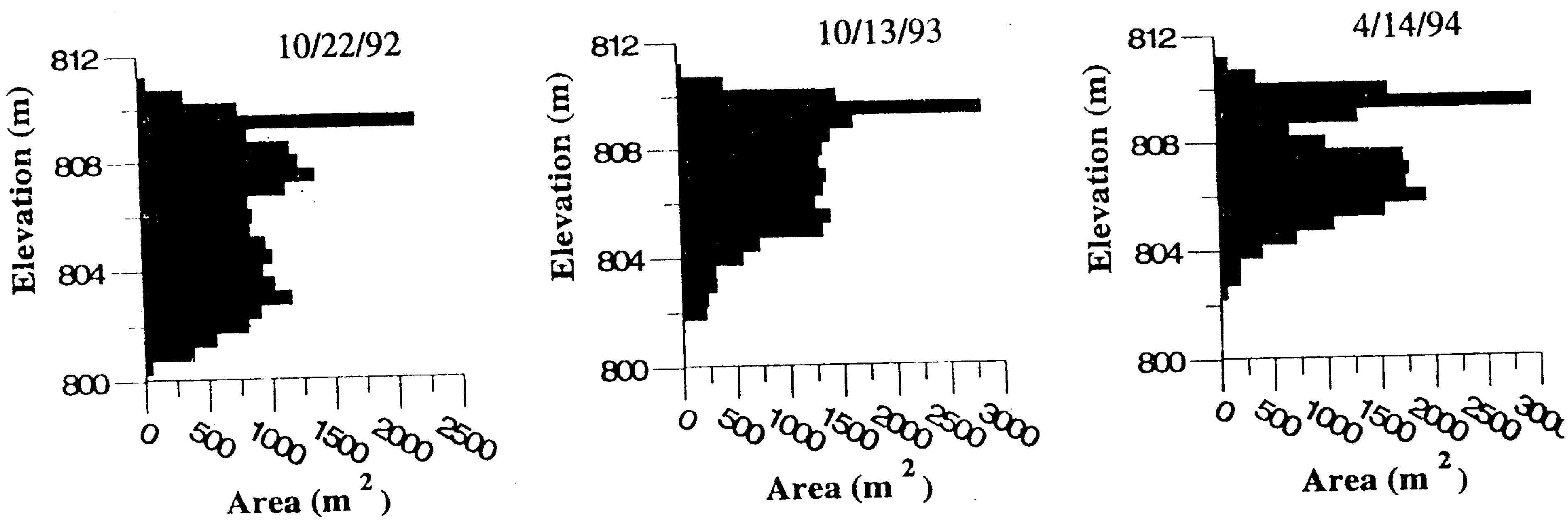

Near-shore P8
v.e.= 6:1
Elevation (m)
Distance (m)
100
98
96
94
92
90
88
86
60
80
100
120
140


Cross-channel P8
v.e.= 8:1
Elevation (m)
Distance (m)
100
98
96
94
92
90
88
86
84
82
80
100
120
140
160
180
200
220
07/29/91
10/29/91
10/22/92
04/06/93
10/14/93
04/14/94

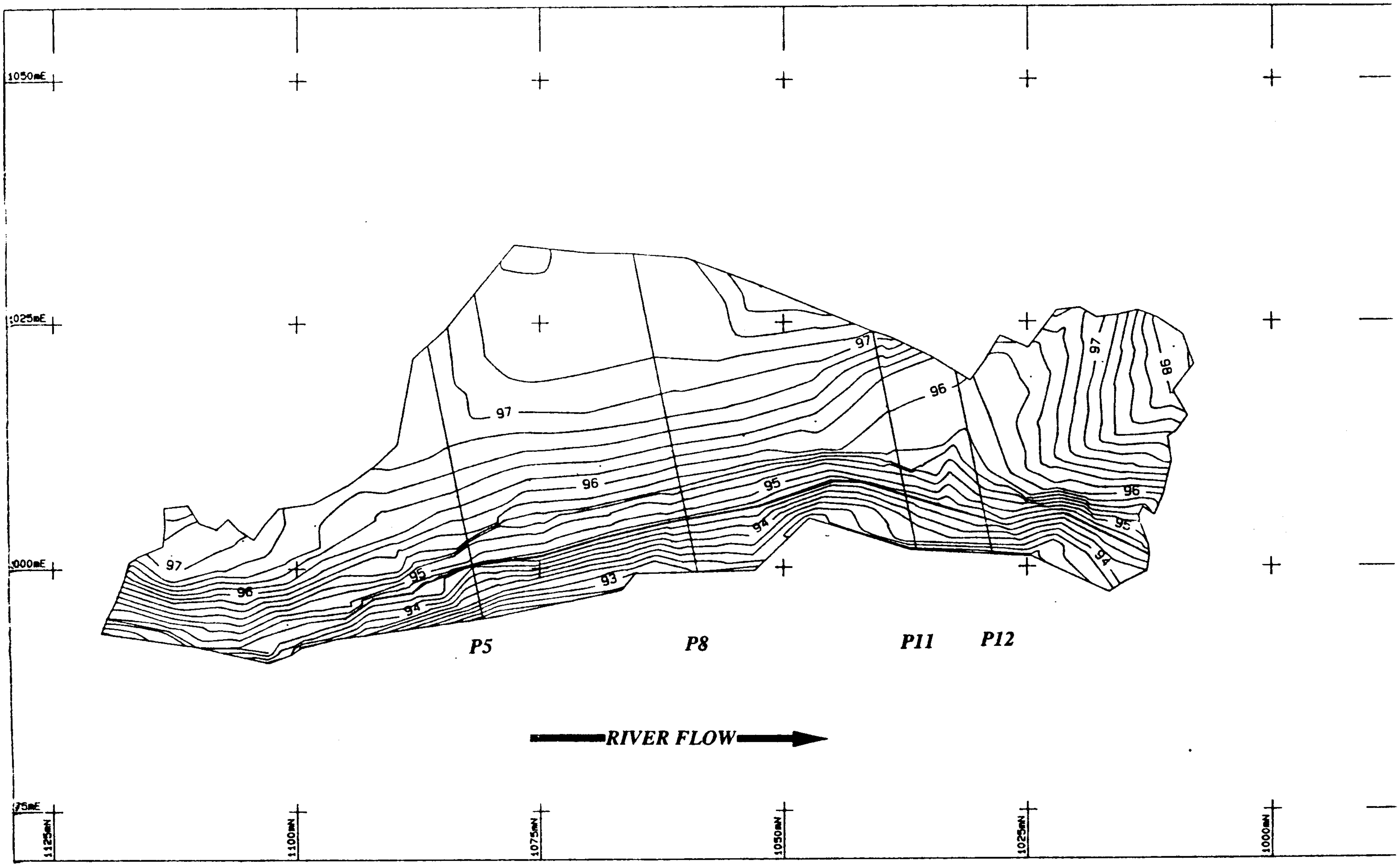

165
130
100
0
-100
% Volume Change
% Area Change
% area
% volume
1/1/91
7/3/91
1/2/92
7/3/92
1/2/93
7/4/93
1/3/94
7/5/94
Time


7000
6000
5000
4000
3000
2000
Volume (m³)
volume
Area
1/1/91
7/3/91
1/2/92
7/3/92
1/2/93
7/4/93
1/3/94
7/5/94
Time


Hypsometric Curves
Relative Height (h/H)
1.0
0.8
0.6
0.4
0.2
0.0
Relative Area (a/A)
0.0
0.2
0.4
0.6
0.8
1.0
10/22/92
10/13/93
4/14/94


10/22/92
10/13/93
4/14/94
Elevation (m)
812
808
804
800
Area (m 2)
0
500
1000
1500
2000
2500
3000


Area of Study
M 81


1050mE
1025mE
1000mE
975mE
1125mN
1100mN
1075mN
1050mN
1025mN
1000mN
97
96
95
94
93
98
P5
P8
P11
P12
RIVER FLOW

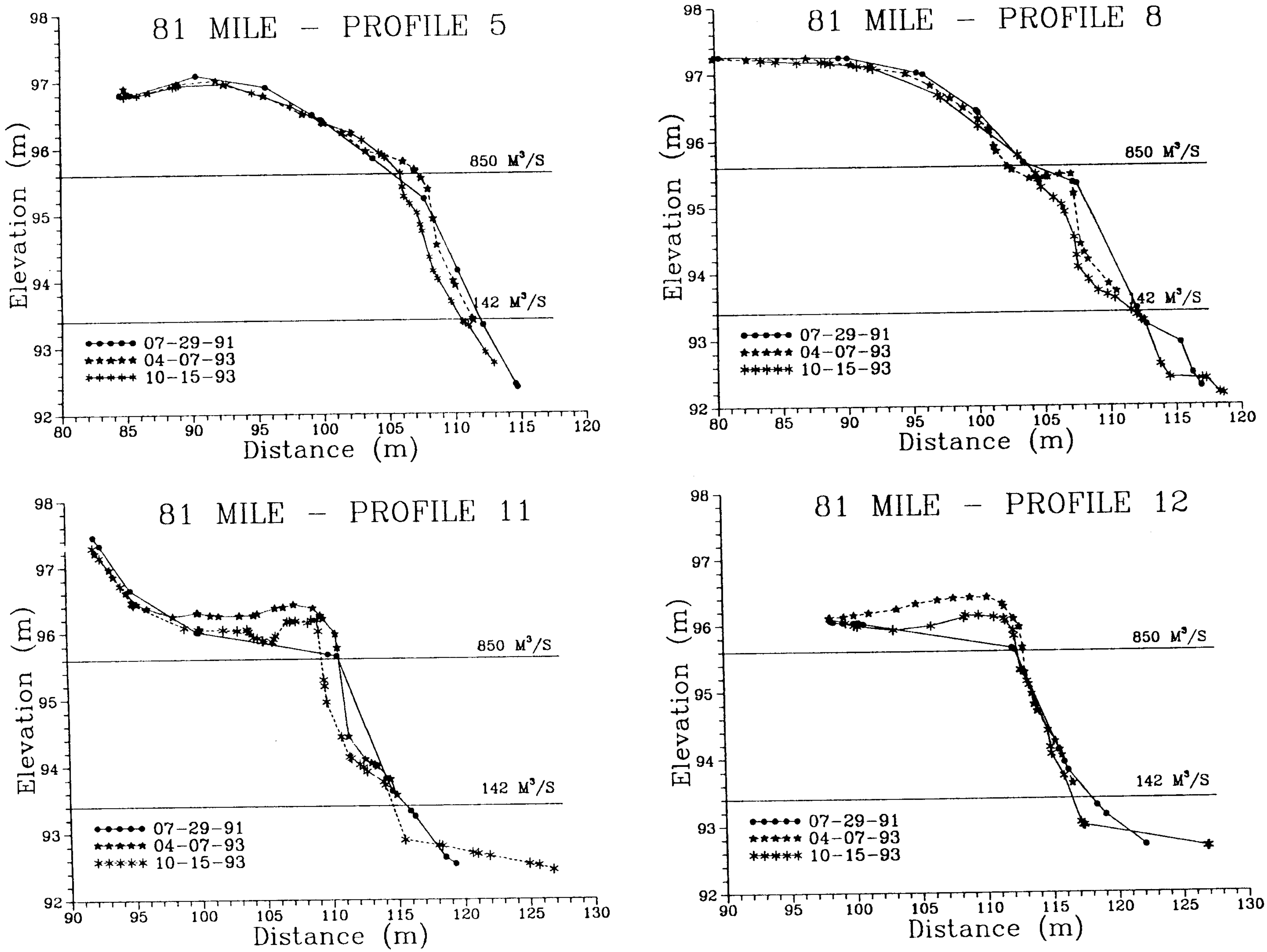
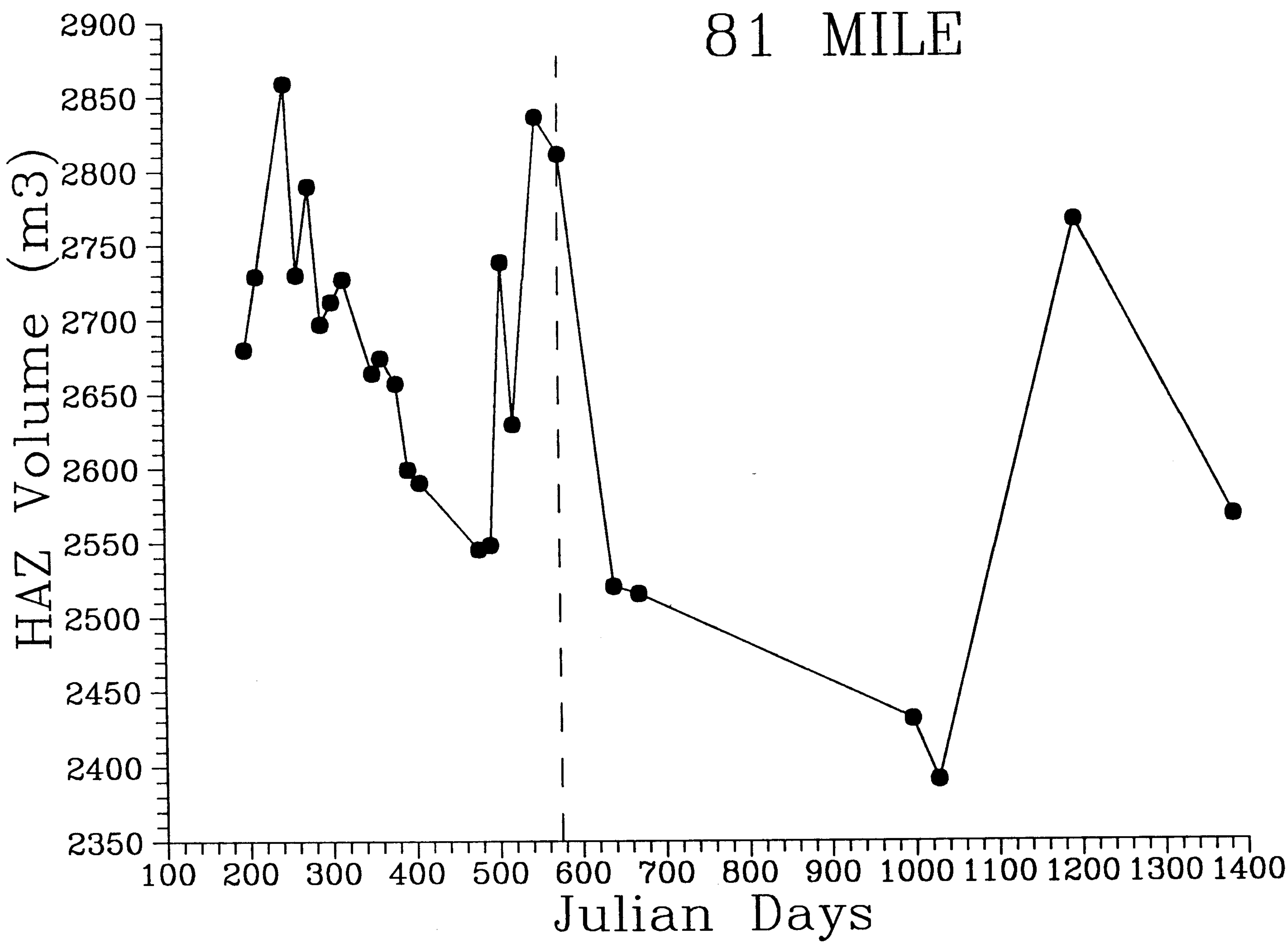
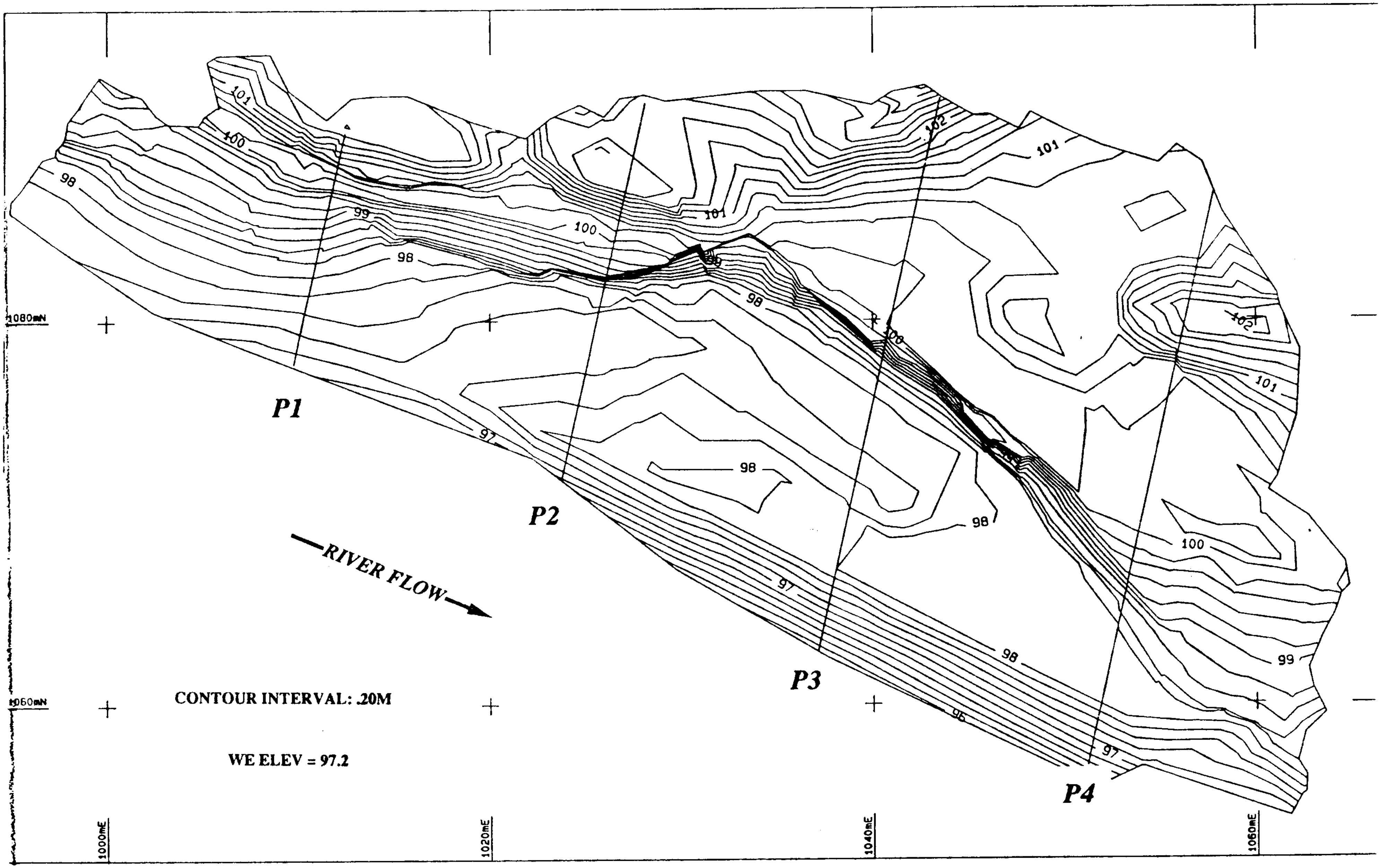


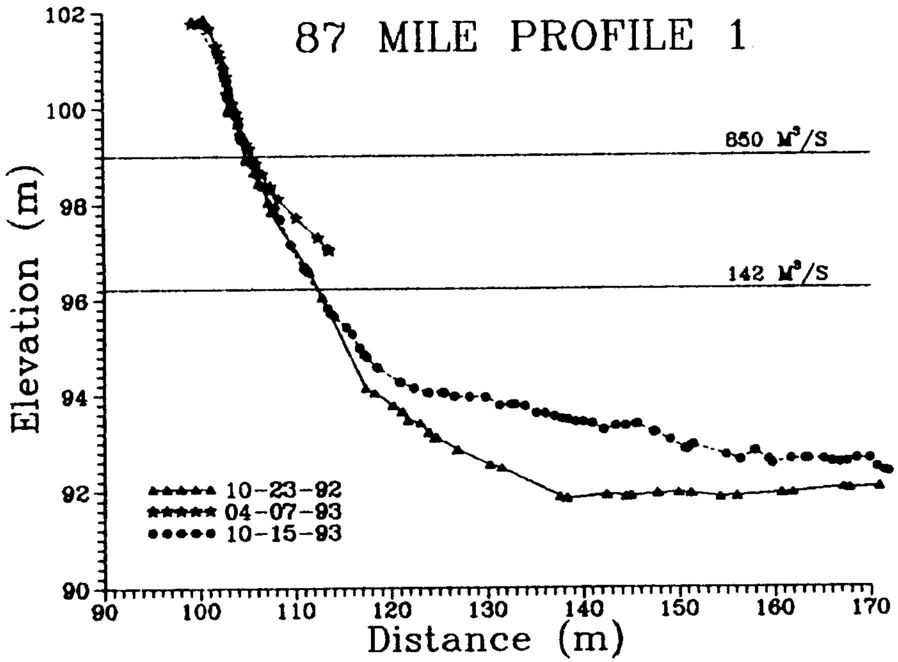
Figure 5. Cont.

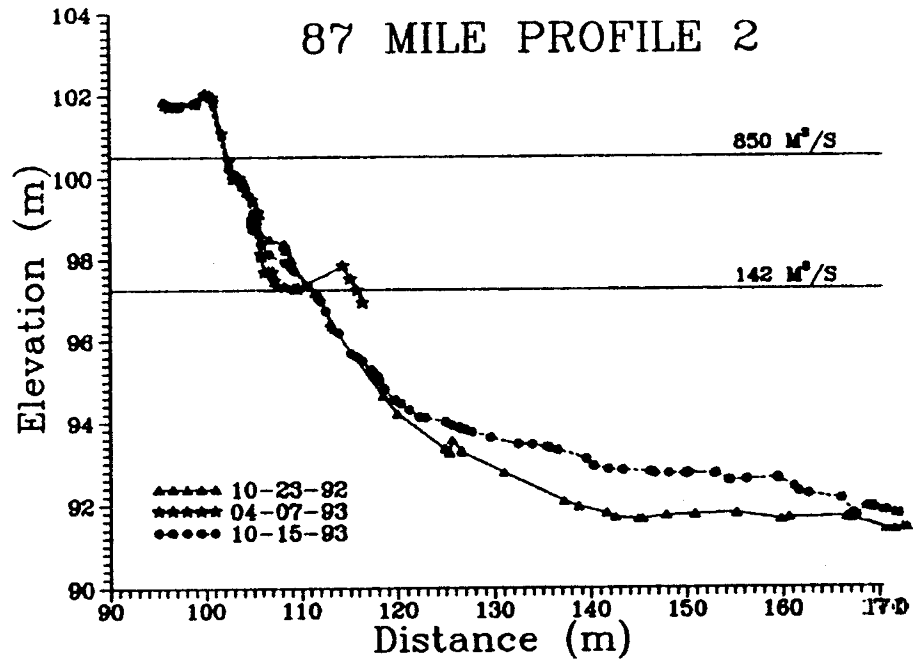

81 MILE
HAZ Volume (m3)
2900
2850
2800
2750
2700
2650
2600
2550
2500
2450
2400
2350
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days

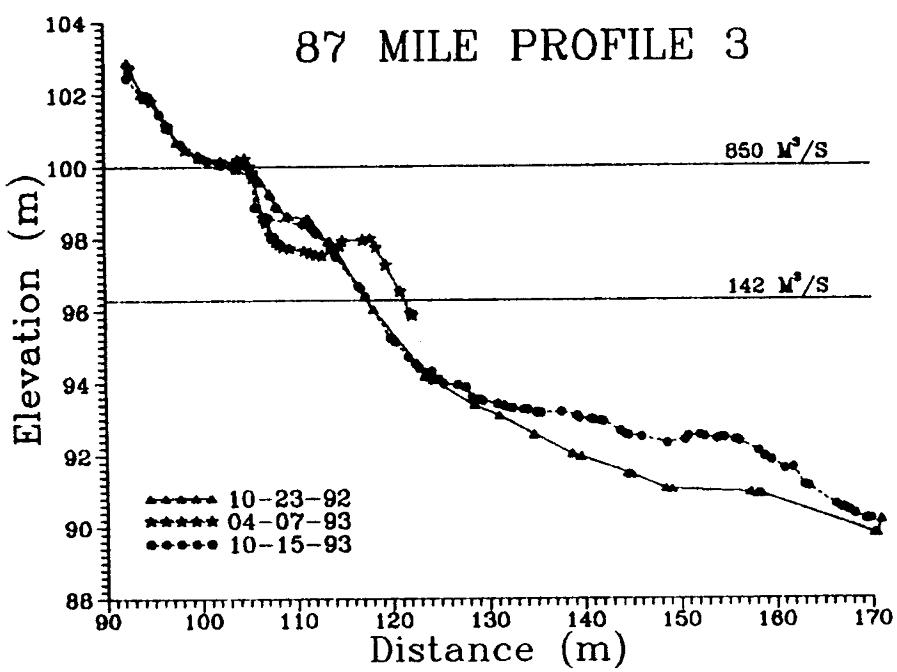

GCES
Area of
RM 87.0

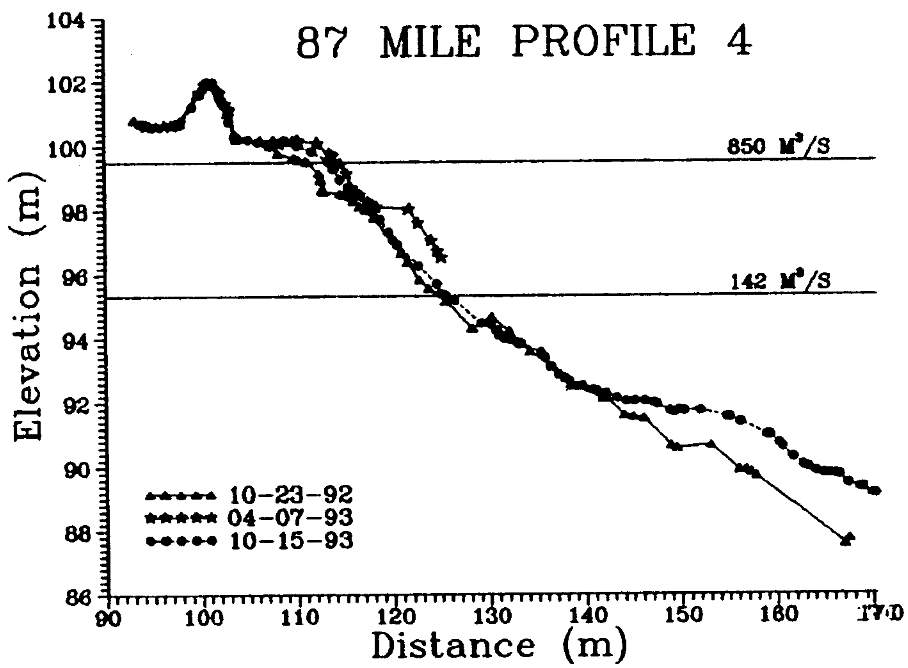


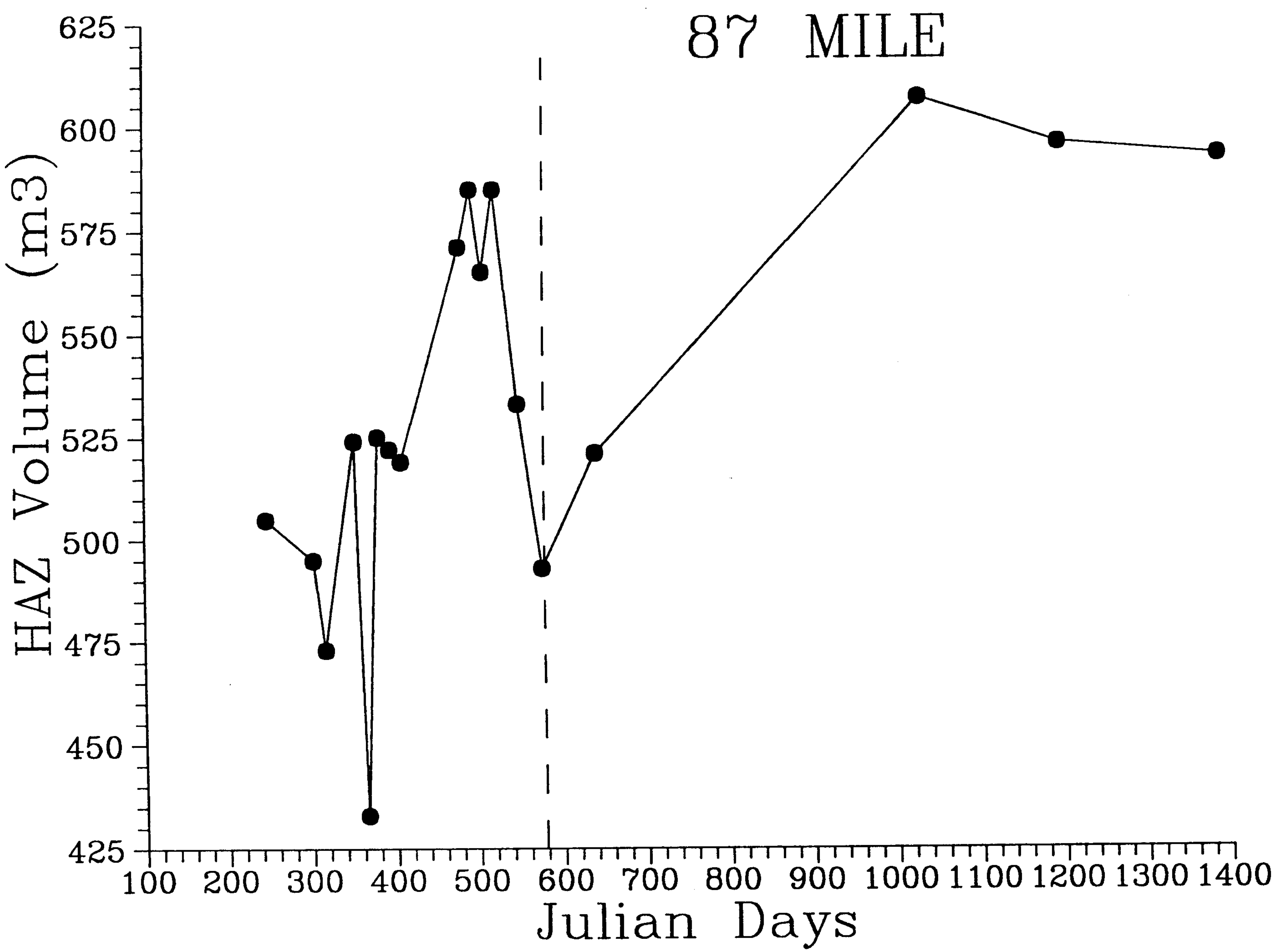
P1
P2
P3
P4
RIVER FLOW
CONTOUR INTERVAL: .20M
WE ELEV = 97.2
1080mN
1060mN
1000mE
1020mE
1040mE
1060mE
101
100
99
98
97
102

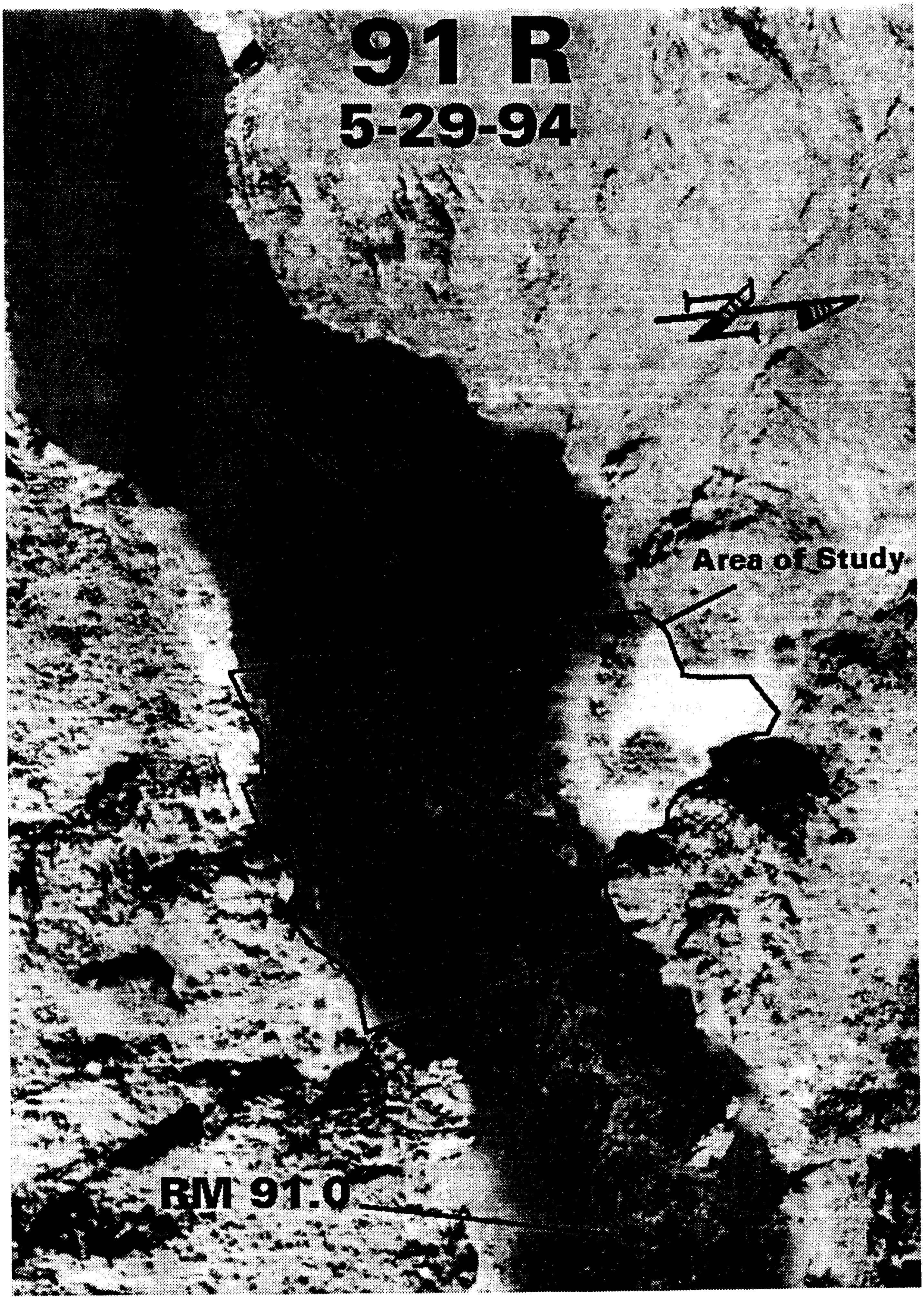

87 MILE PROFILE 1
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-23-92
04-07-93
10-15-93

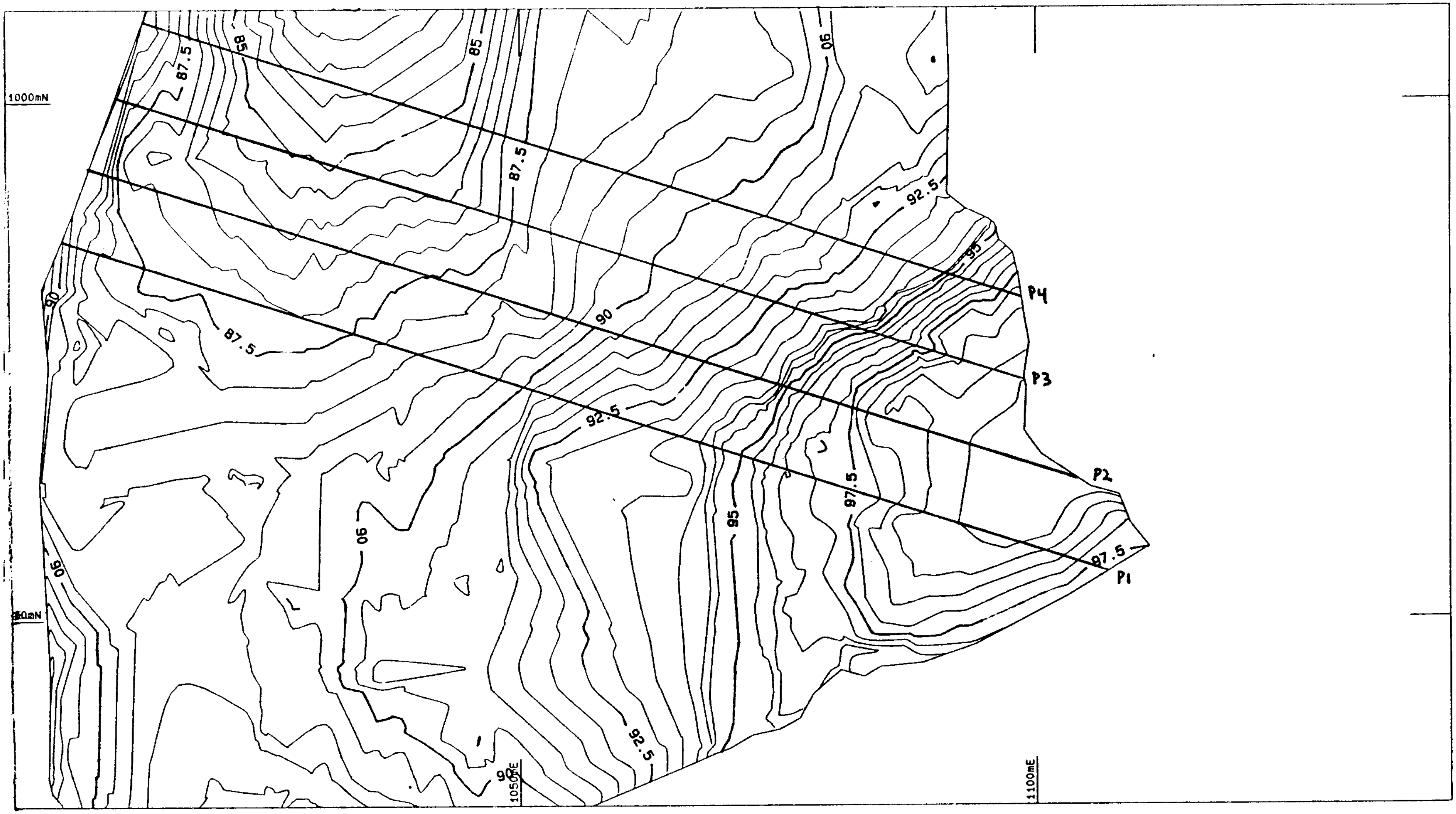

87 MILE PROFILE 2
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-23-92
04-07-93
10-15-93


87 MILE PROFILE 3
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-23-92
04-07-93
10-15-93

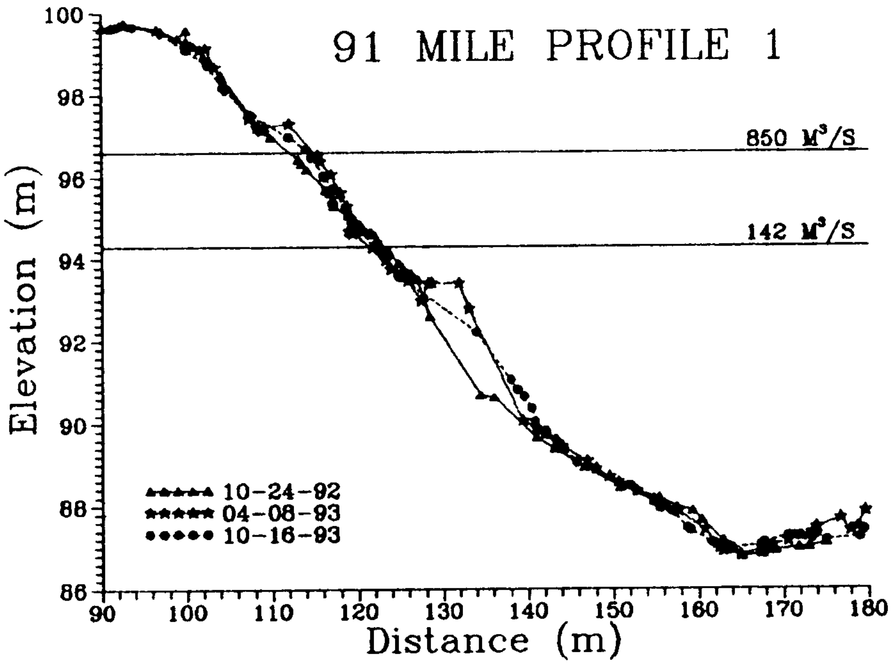

87 MILE PROFILE 4
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
10-23-92
04-07-93
10-15-93

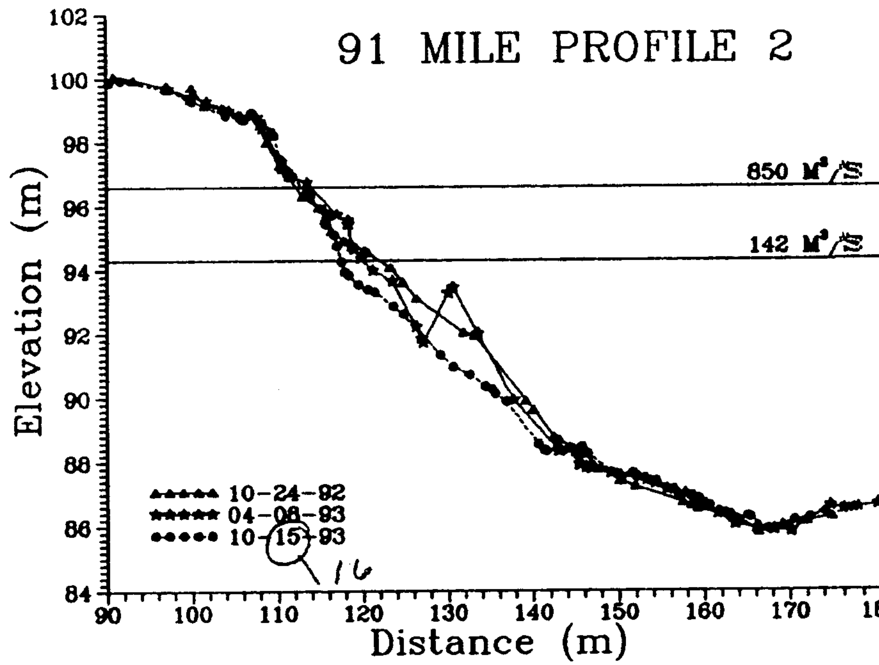

87 MILE
HAZ Volume (m3)
625
600
575
550
525
500
475
450
425
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

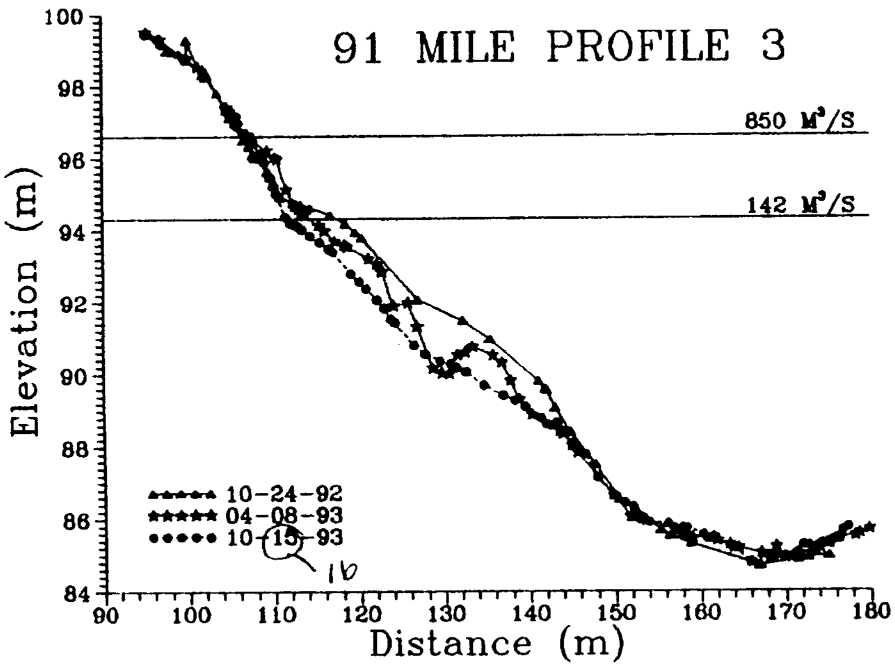

91 R
5-29-94
N
Area of Study
RM 91.0

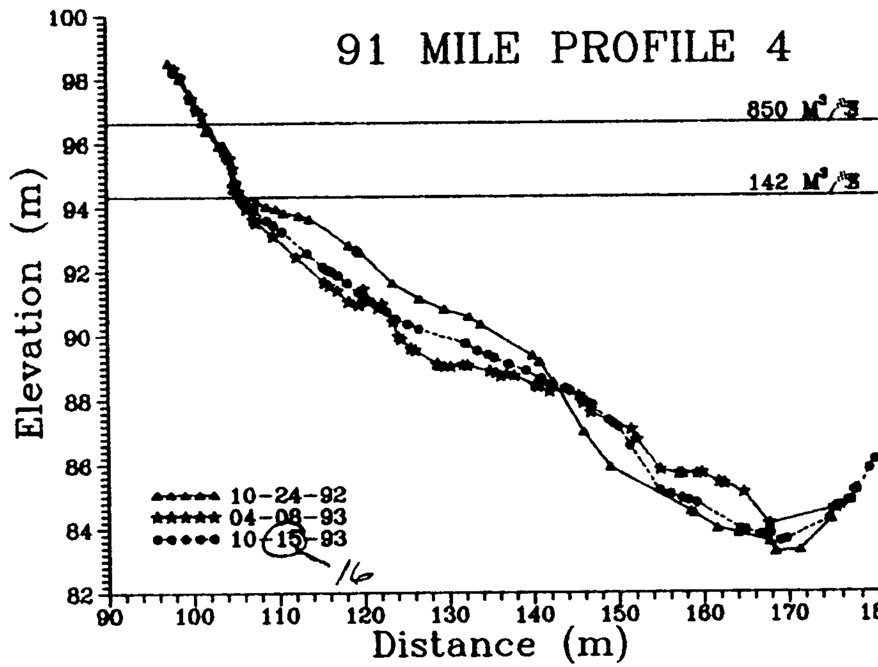


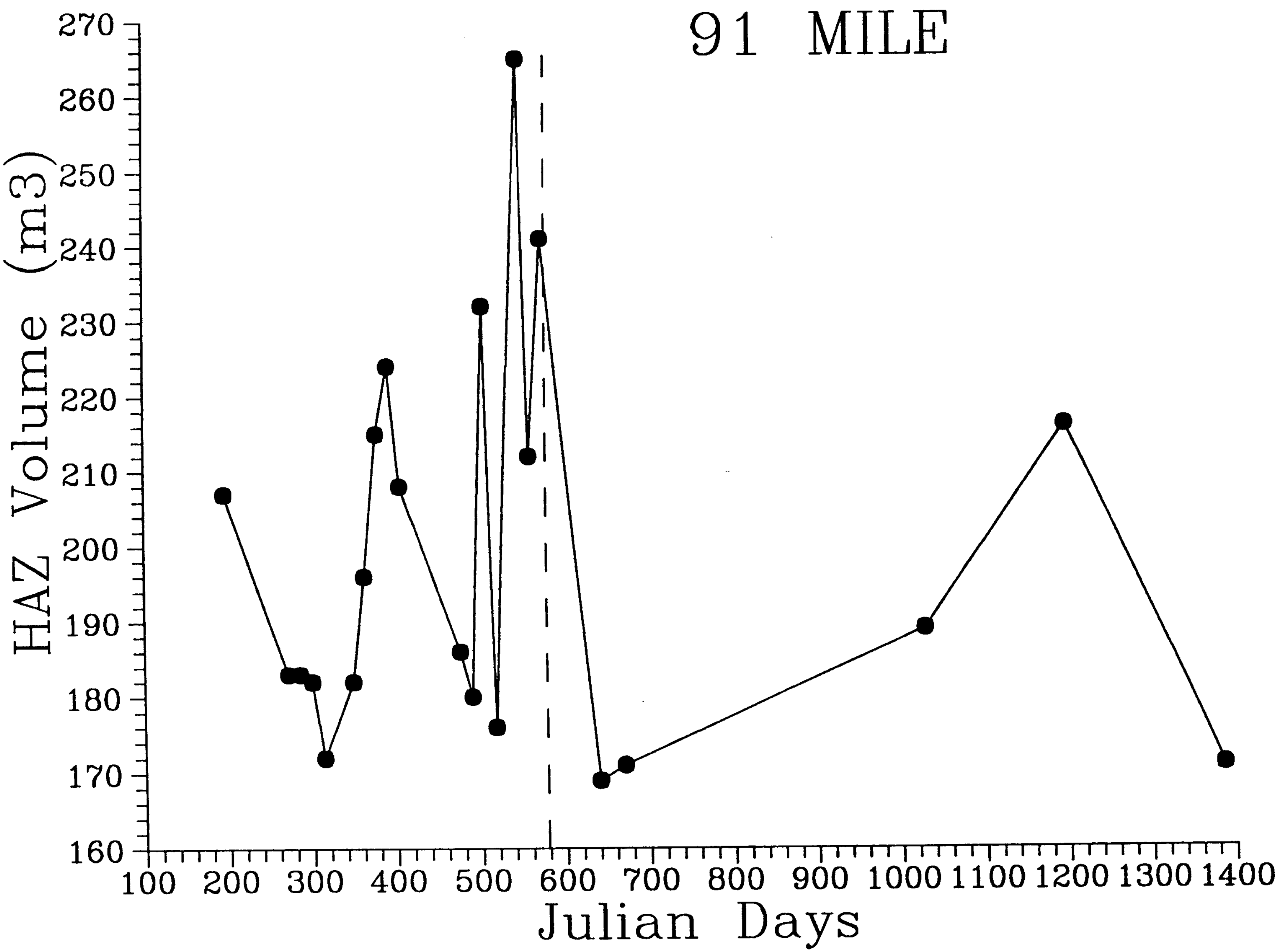
GCES BEACH SURVEY B18 91R-B18 91 MILE 10-16-93 1: 350


91 MILE PROFILE 1
850 M³/S
142 M³/S
10-24-92
04-08-93
10-16-93
Elevation (m)
Distance (m)

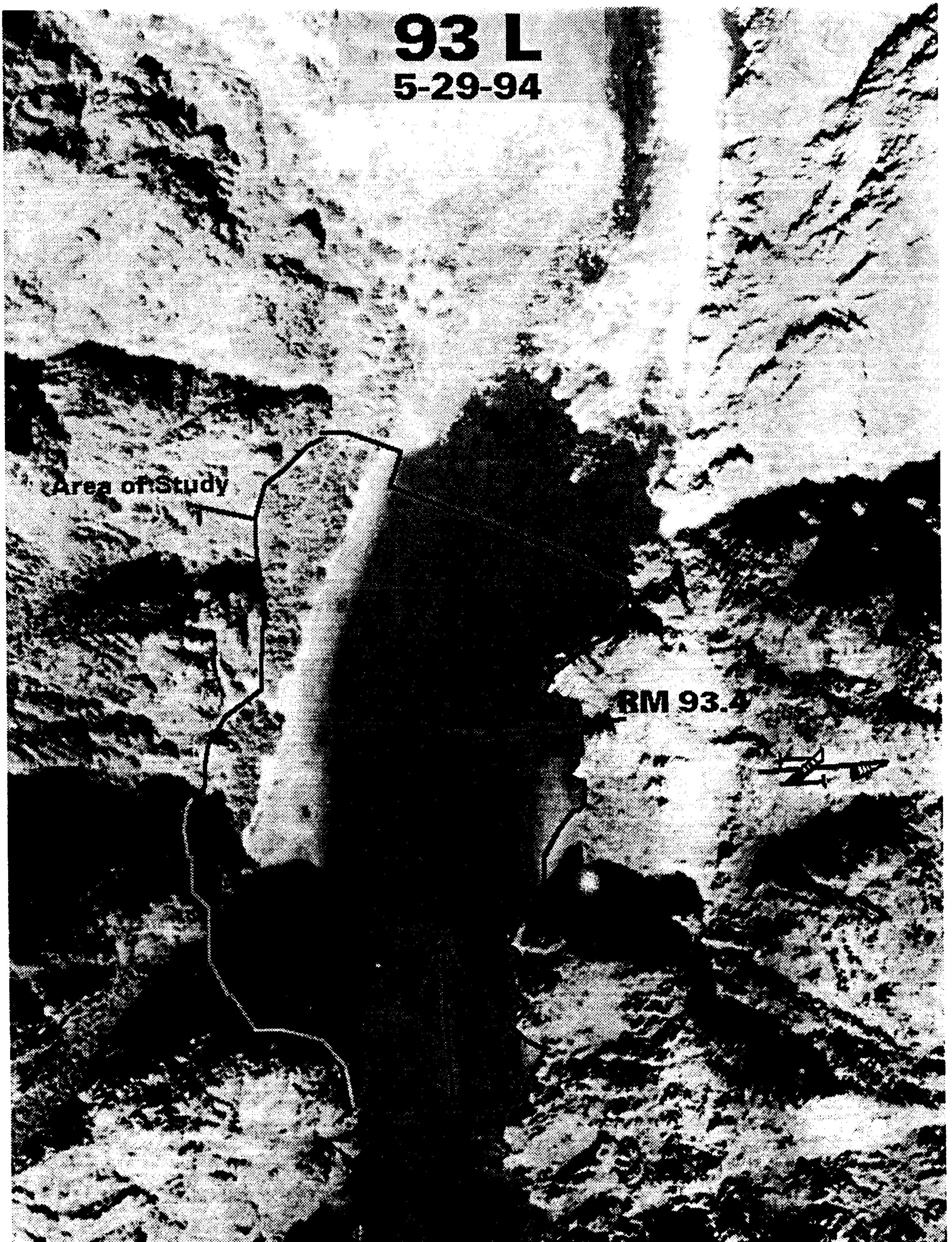

91 MILE PROFILE 2
850 M³/S
142 M³/S
10-24-92
04-08-93
10-15-93
16
Elevation (m)
Distance (m)

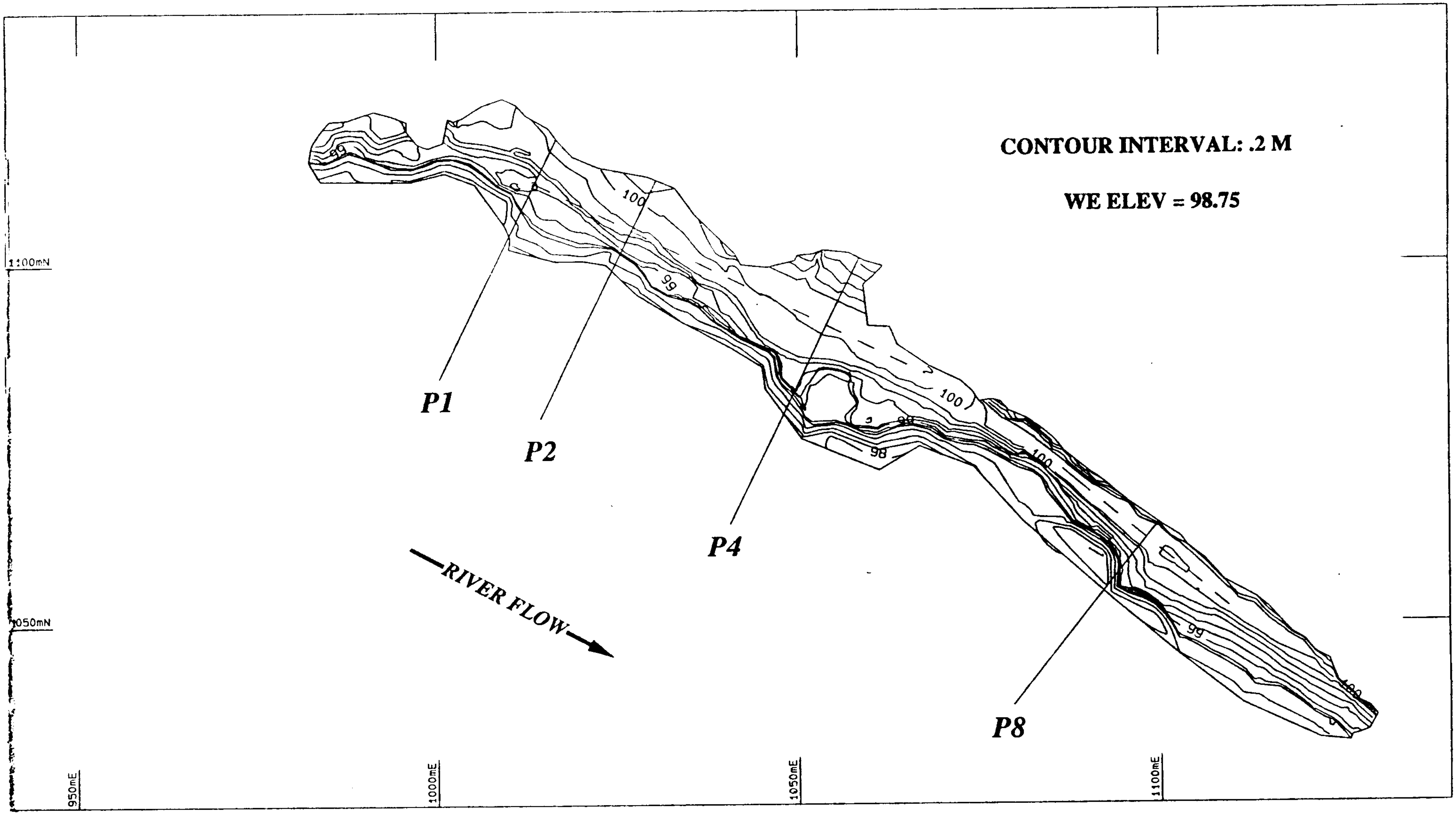

91 MILE PROFILE 3
850 M³/S
142 M³/S
10-24-92
04-08-93
10-15-93
16
Elevation (m)
Distance (m)


91 MILE PROFILE 4
850 M³/S
142 M³/S
10-24-92
04-08-93
10-15-93
16
Elevation (m)
Distance (m)

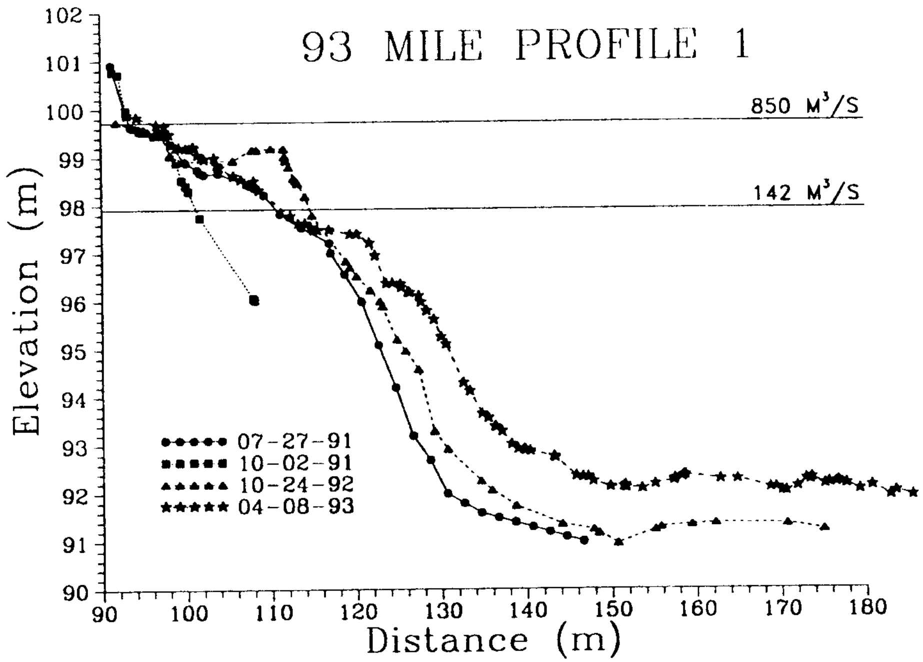


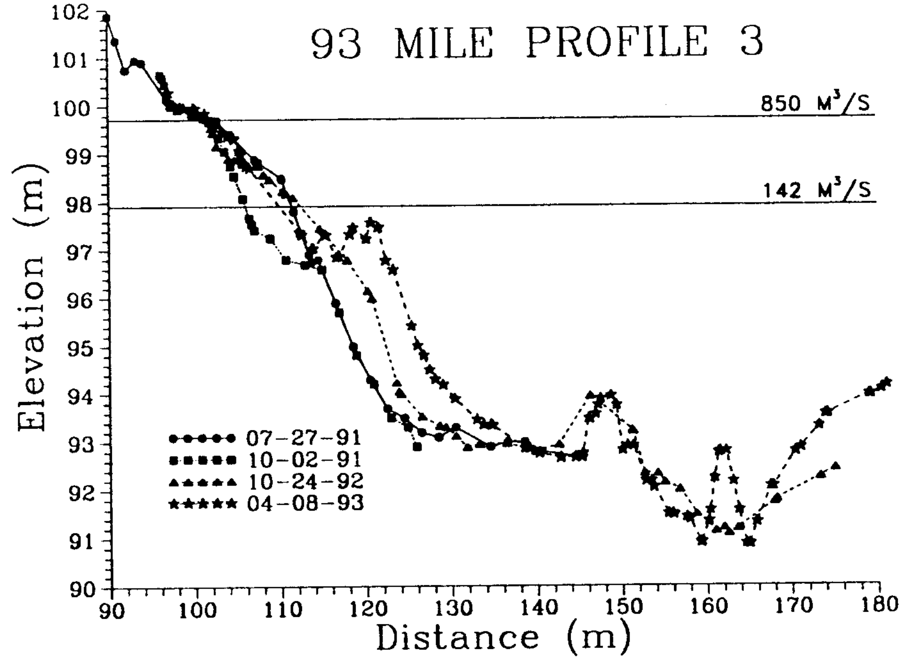
91 MILE
HAZ Volume (m3)
270
260
250
240
230
220
210
200
190
180
170
160
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

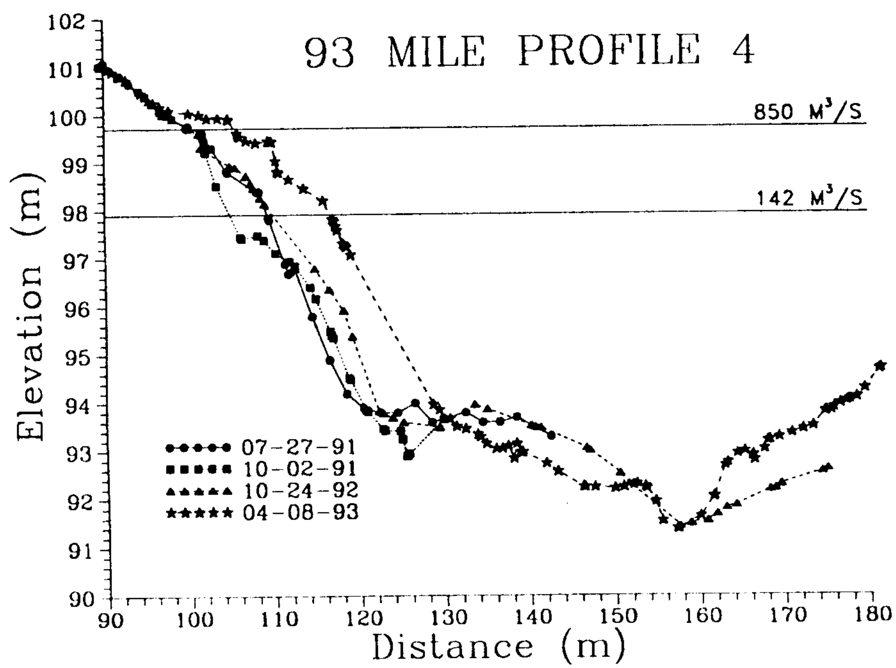

93 L
5-29-94
Area of Study
RM 93.4

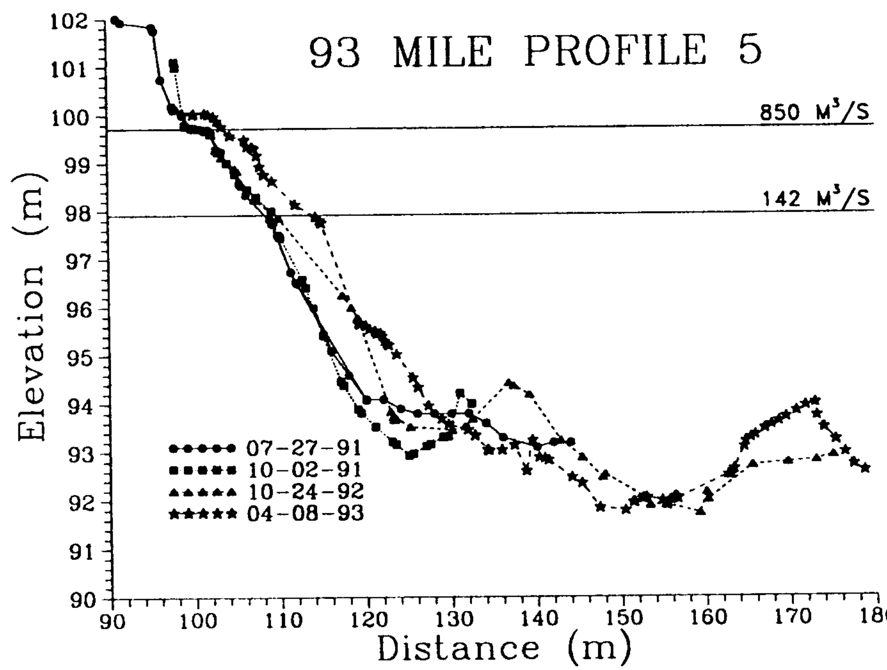


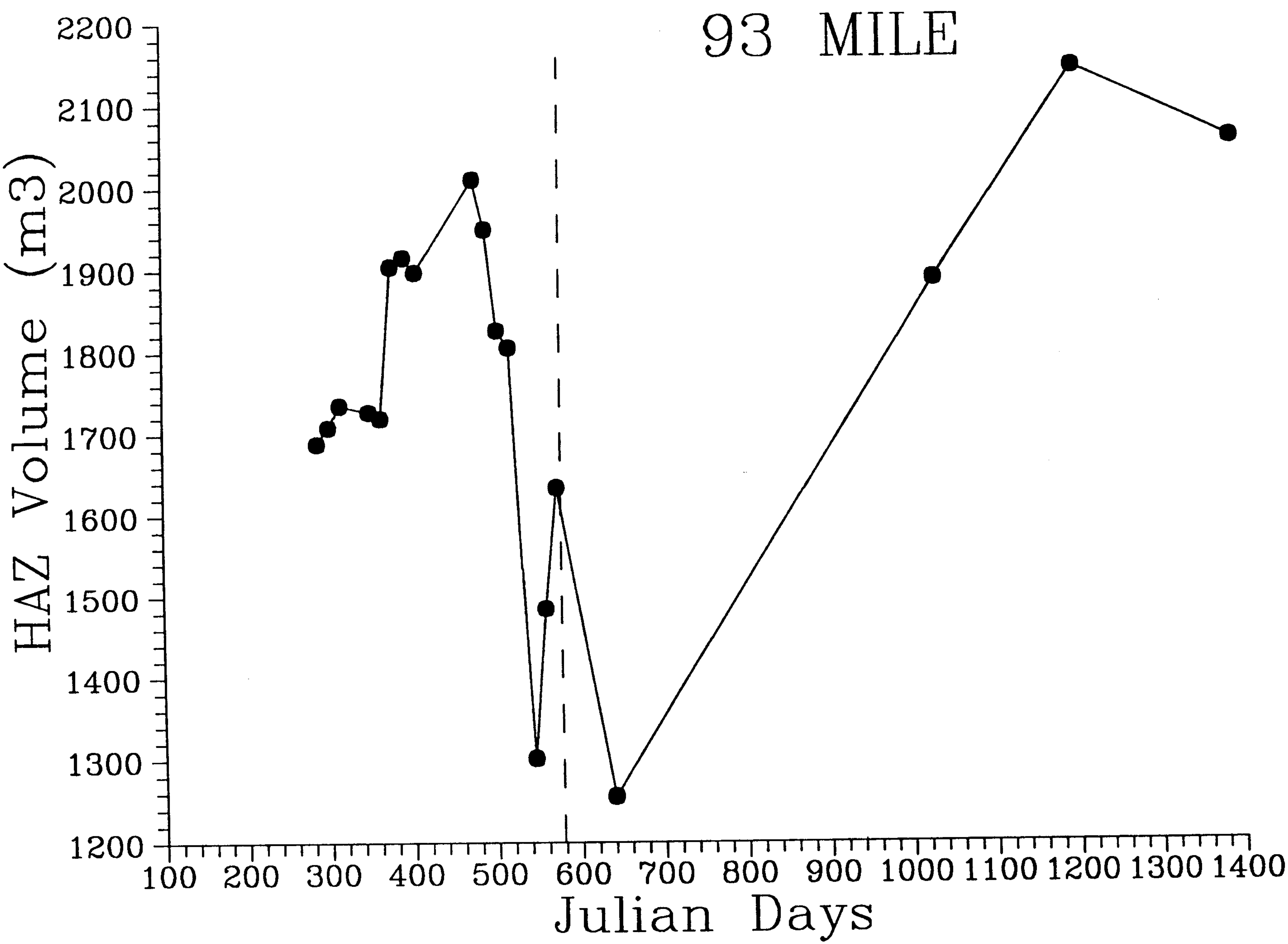
GCES BEACH SURVEY 19Z 93L PROFILES 93 MILE 4-08-93 1: 500

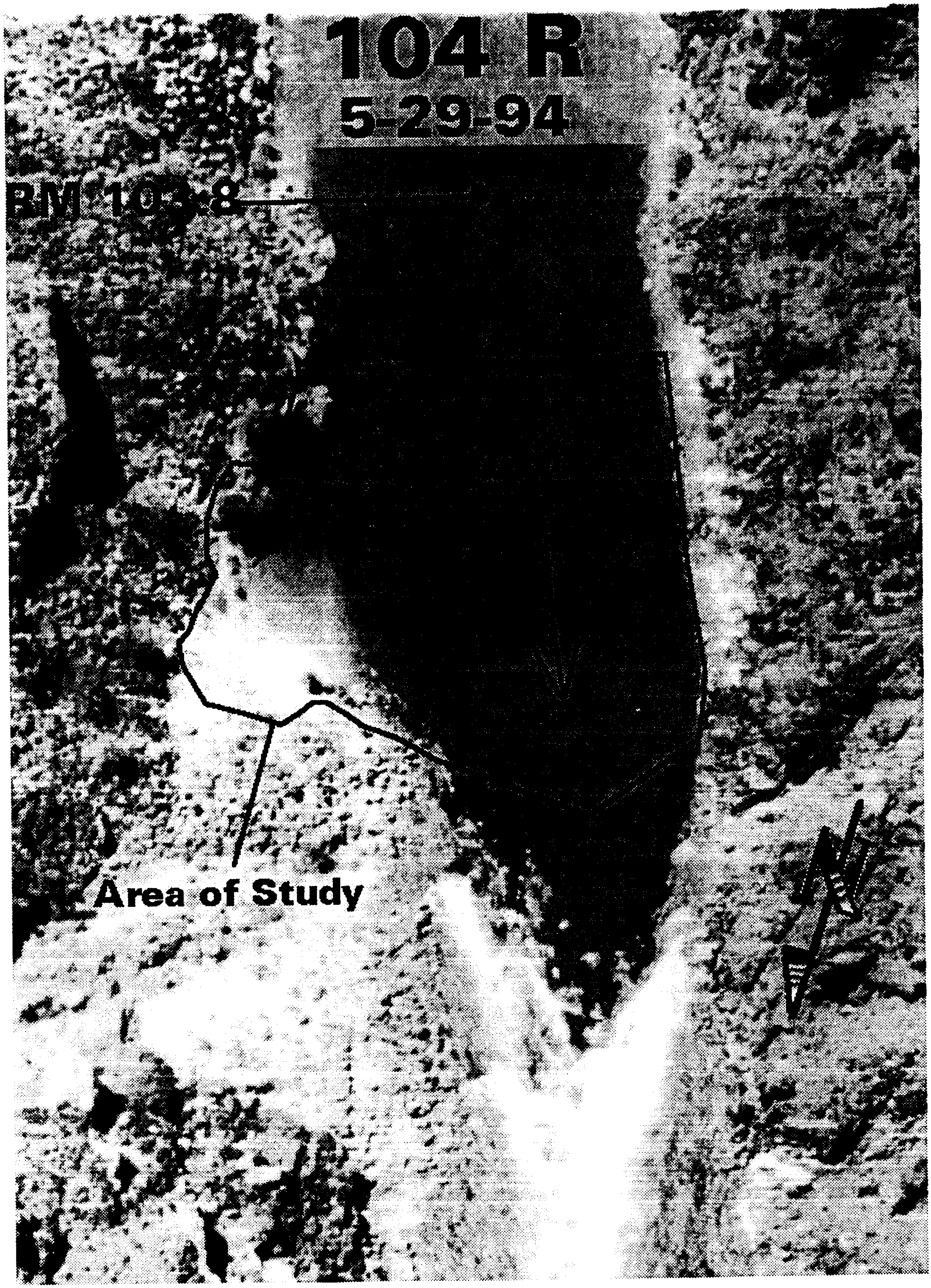

93 MILE PROFILE 1
850 M³/S
142 M³/S
07-27-91
10-02-91
10-24-92
04-08-93
Elevation (m)
Distance (m)

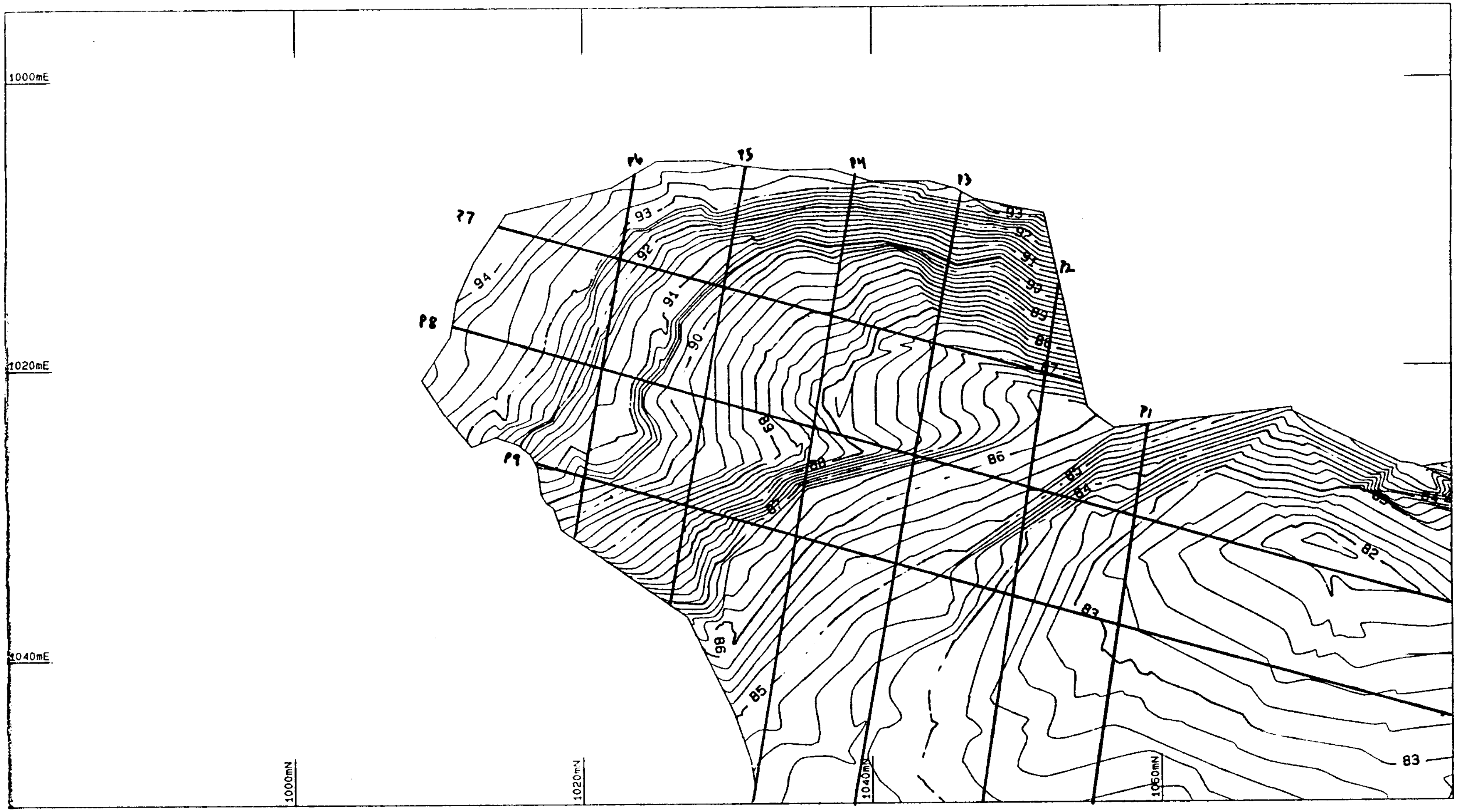

93 MILE PROFILE 3
850 M³/S
142 M³/S
07-27-91
10-02-91
10-24-92
04-08-93
Elevation (m)
Distance (m)


93 MILE PROFILE 4
850 M³/S
142 M³/S
07-27-91
10-02-91
10-24-92
04-08-93
Elevation (m)
Distance (m)

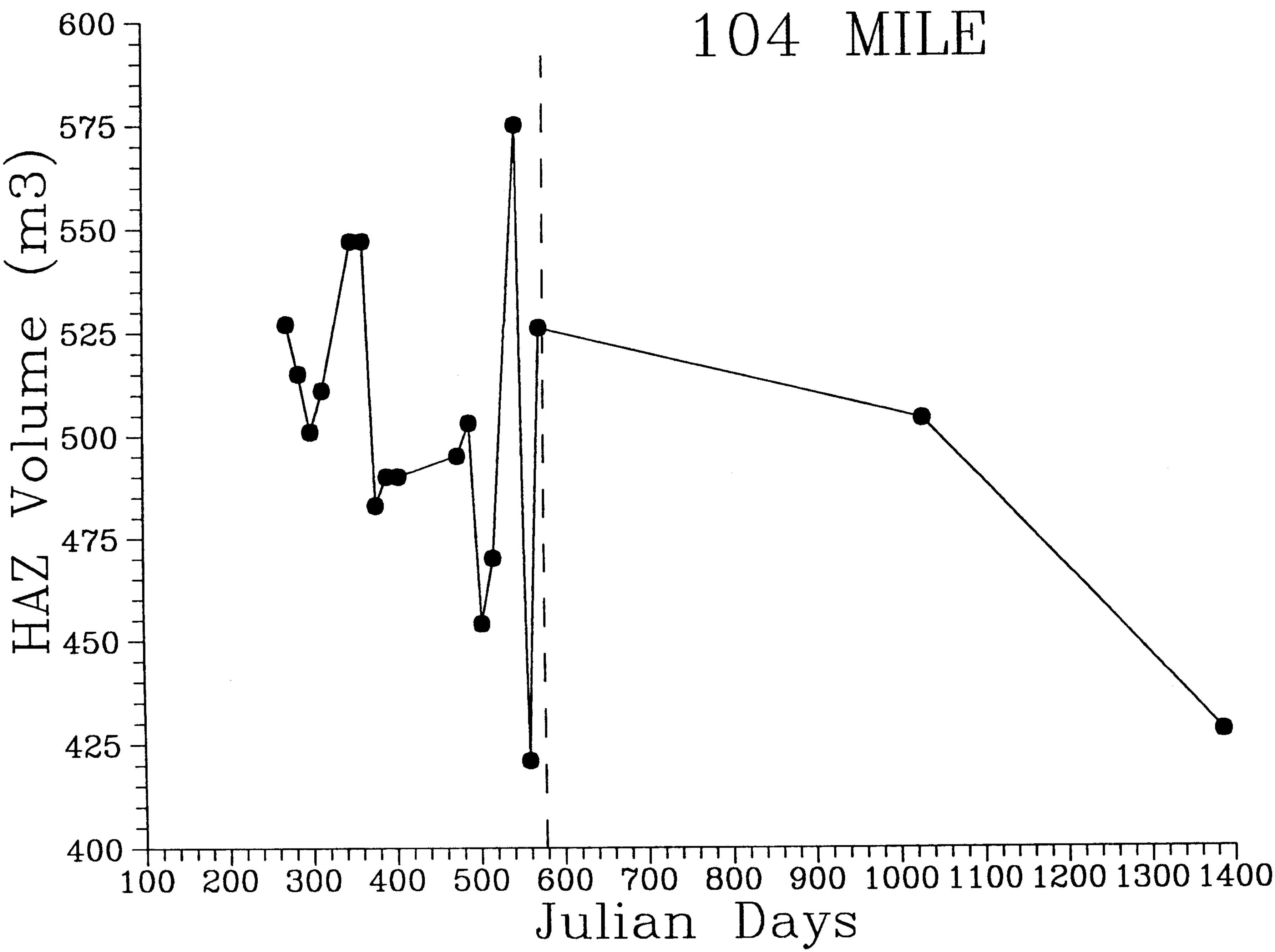

93 MILE PROFILE 5
850 M³/S
142 M³/S
07-27-91
10-02-91
10-24-92
04-08-93
Elevation (m)
Distance (m)

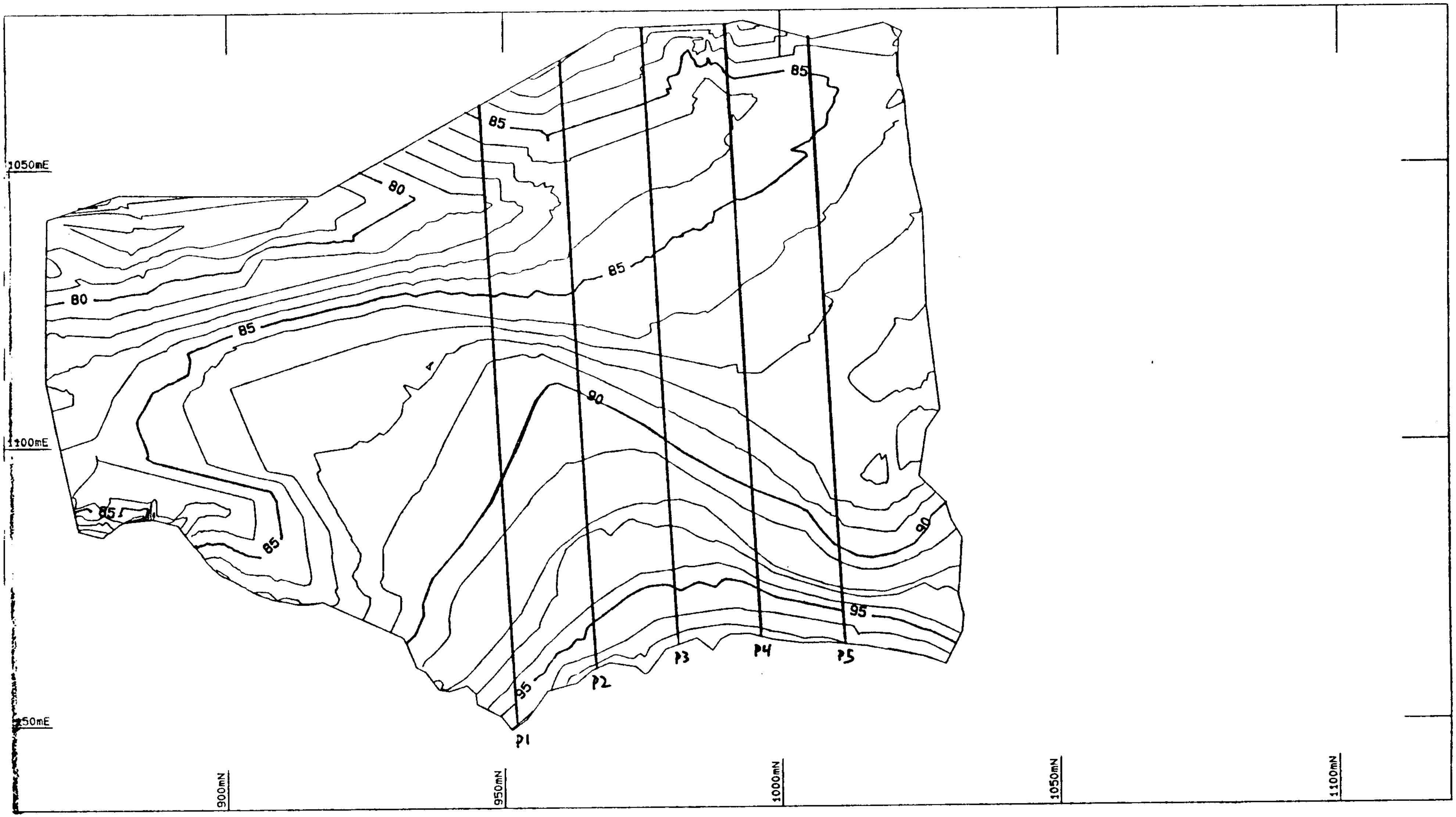

93 MILE
HAZ Volume (m3)
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days


104 R
5-29-94
RM 103.8
Area of Study

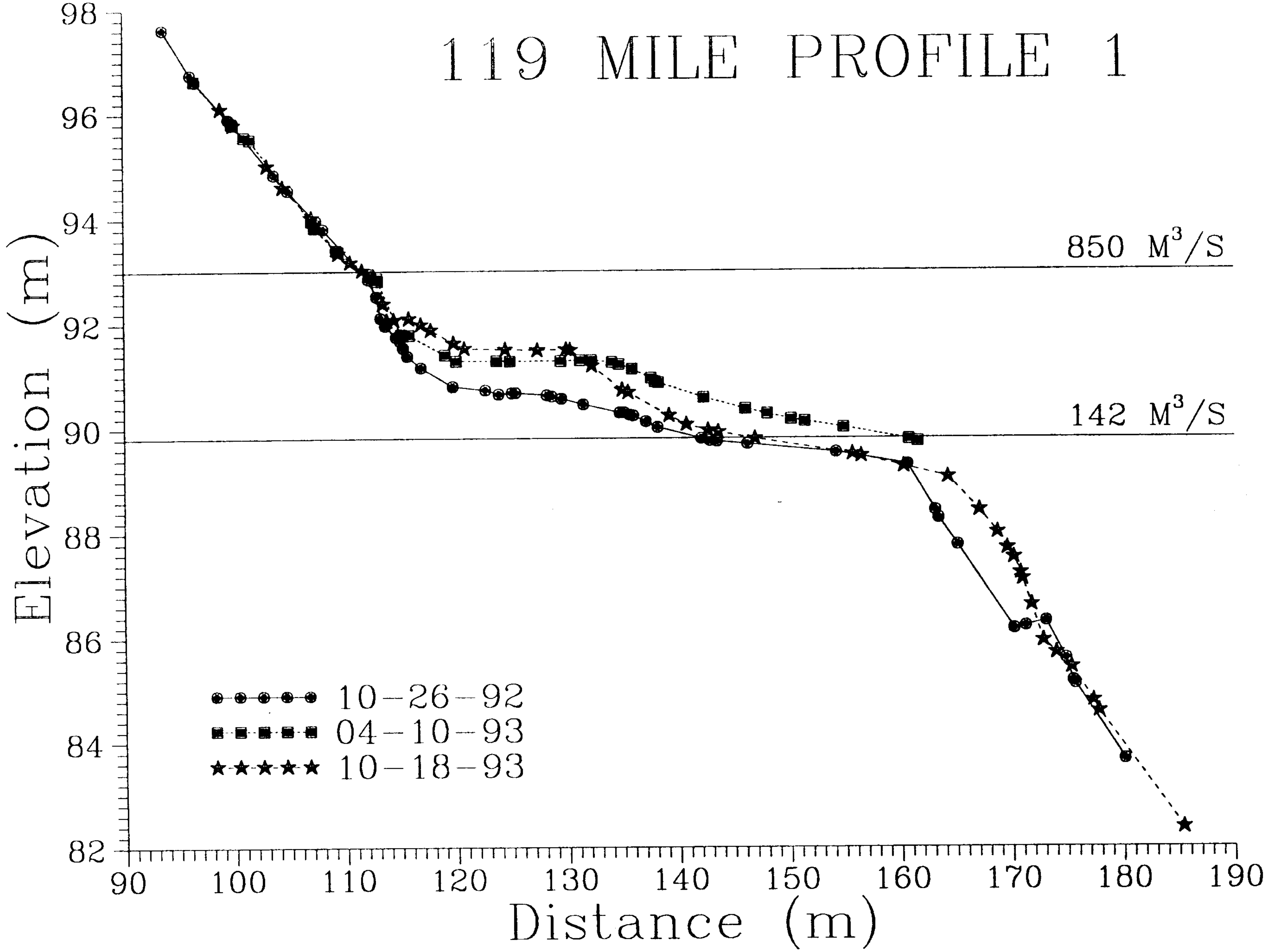


GCES BEACH SURVEY B20 104R-B20 104 MILE 10-17-93 1: 250

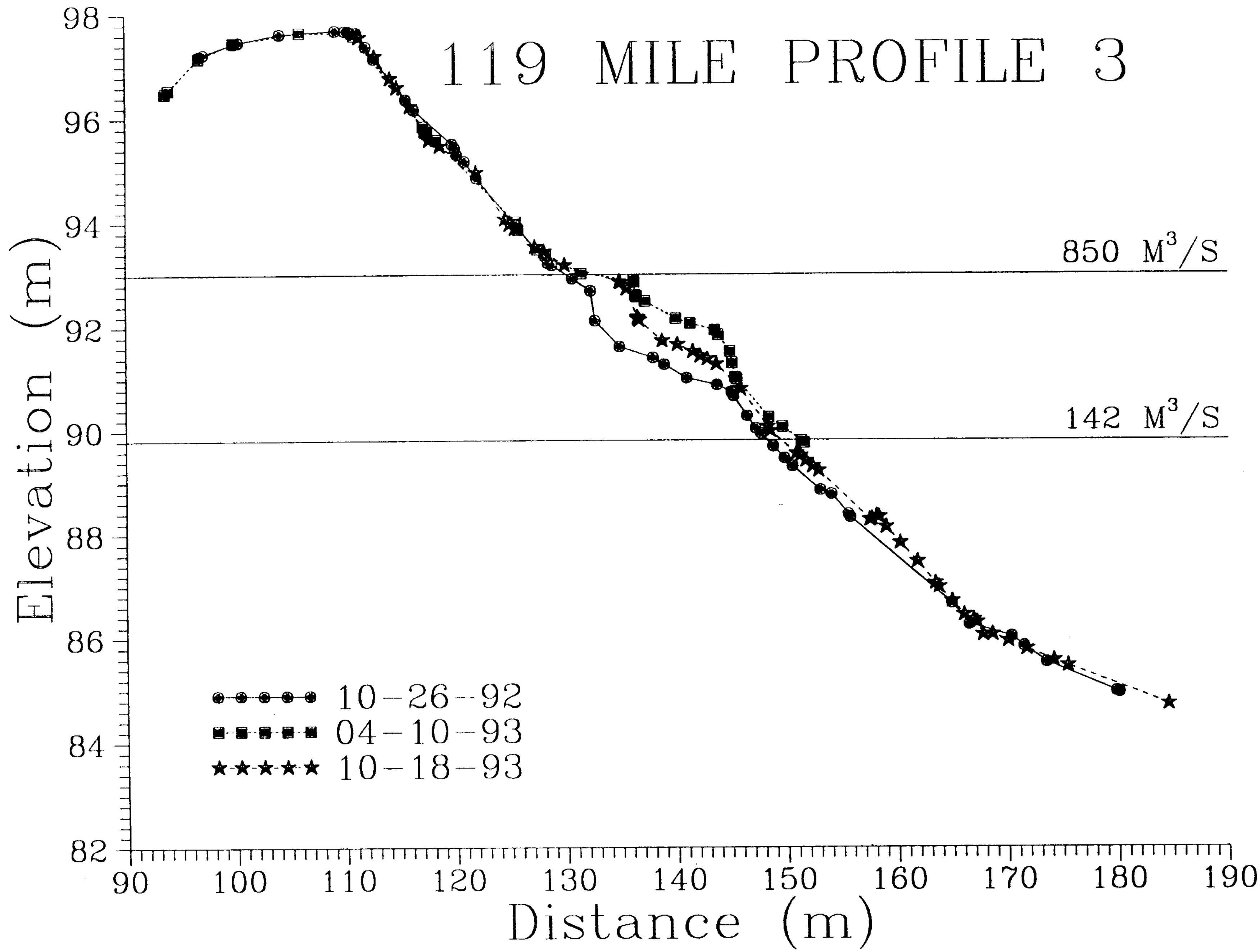

104 MILE
HAZ Volume (m3)
600
575
550
525
500
475
450
425
400
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days

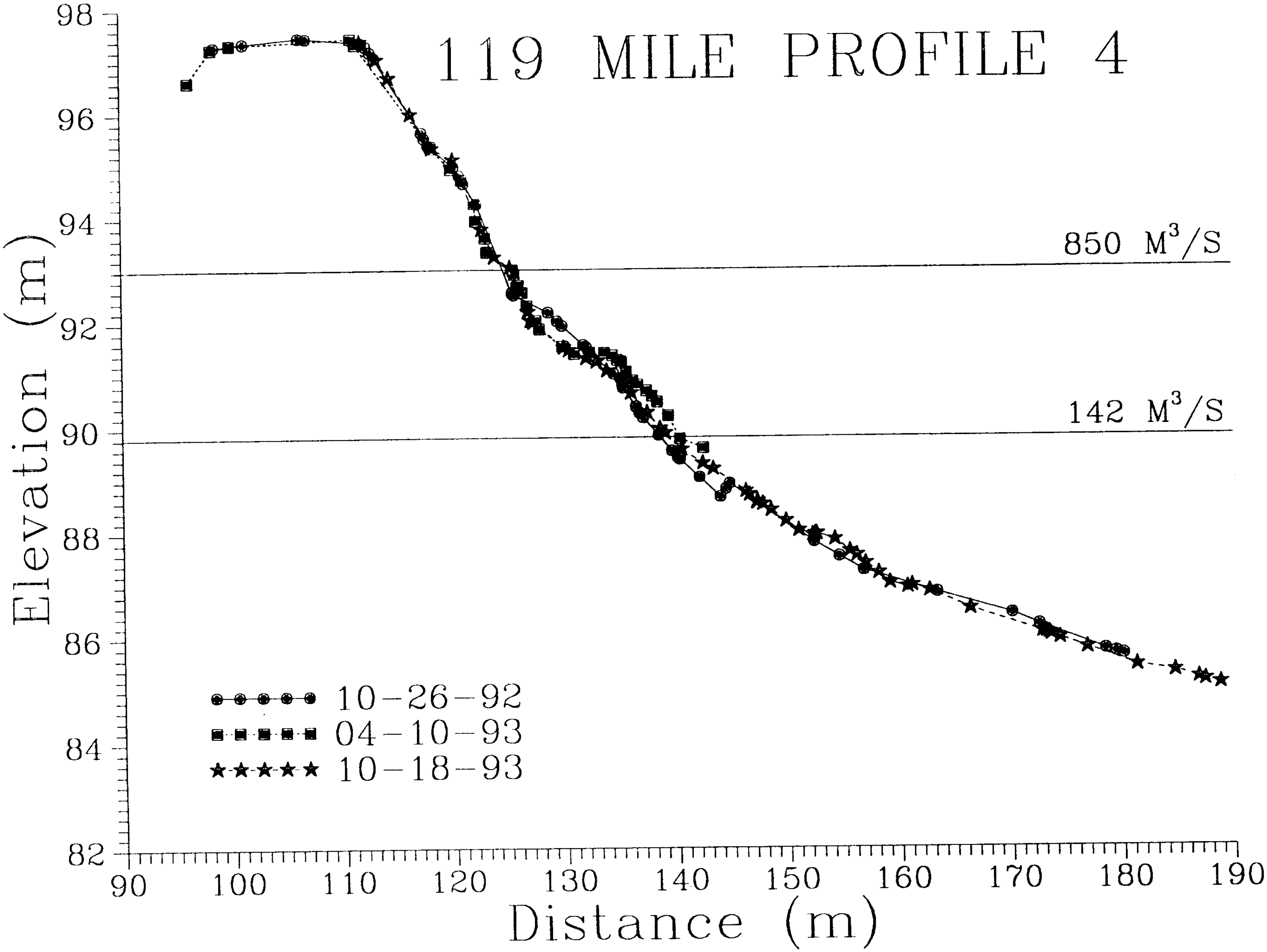


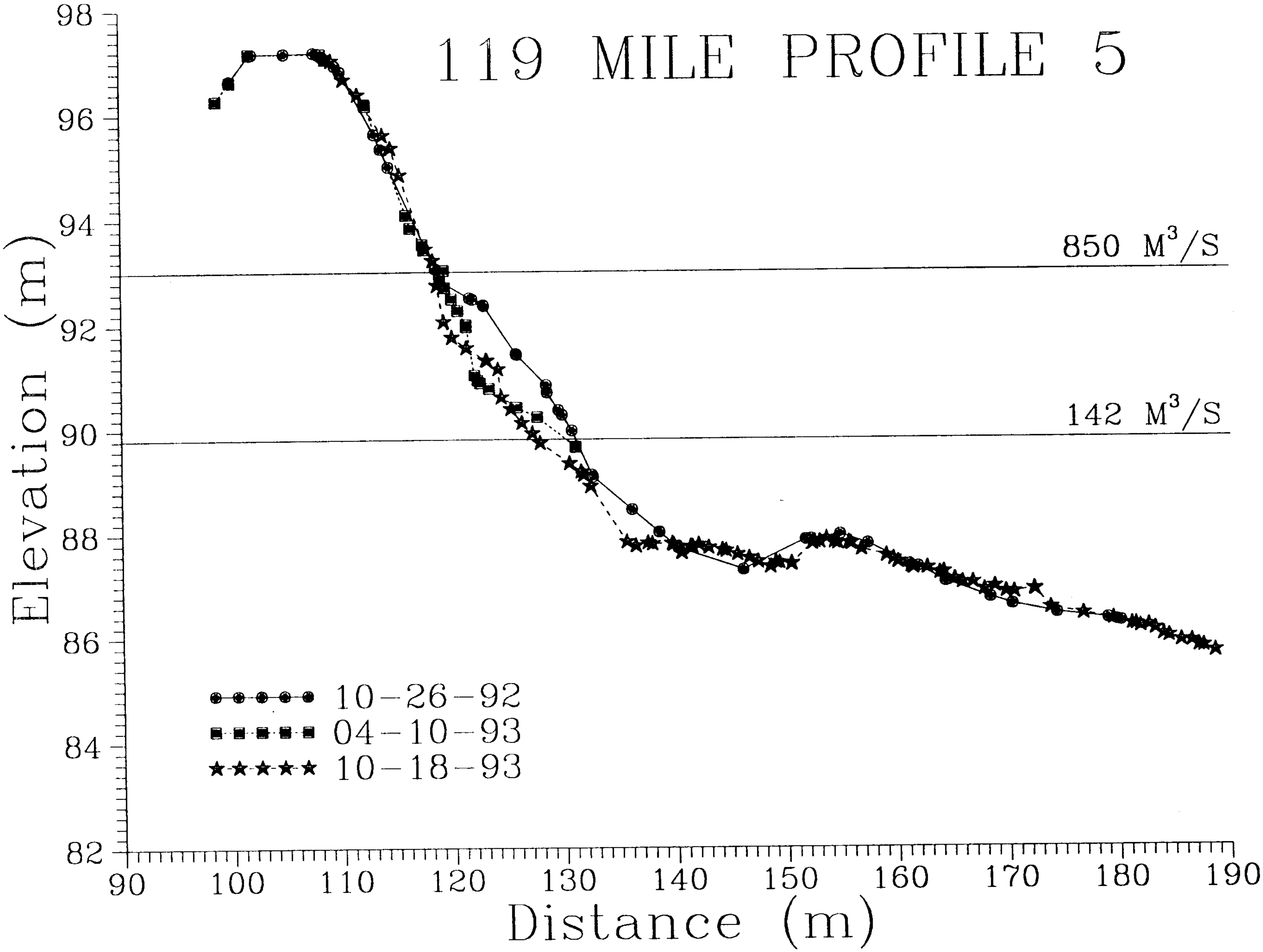
GCES BEACH SURVEY B21 119R-B21 119R 10-18-93 1: 650



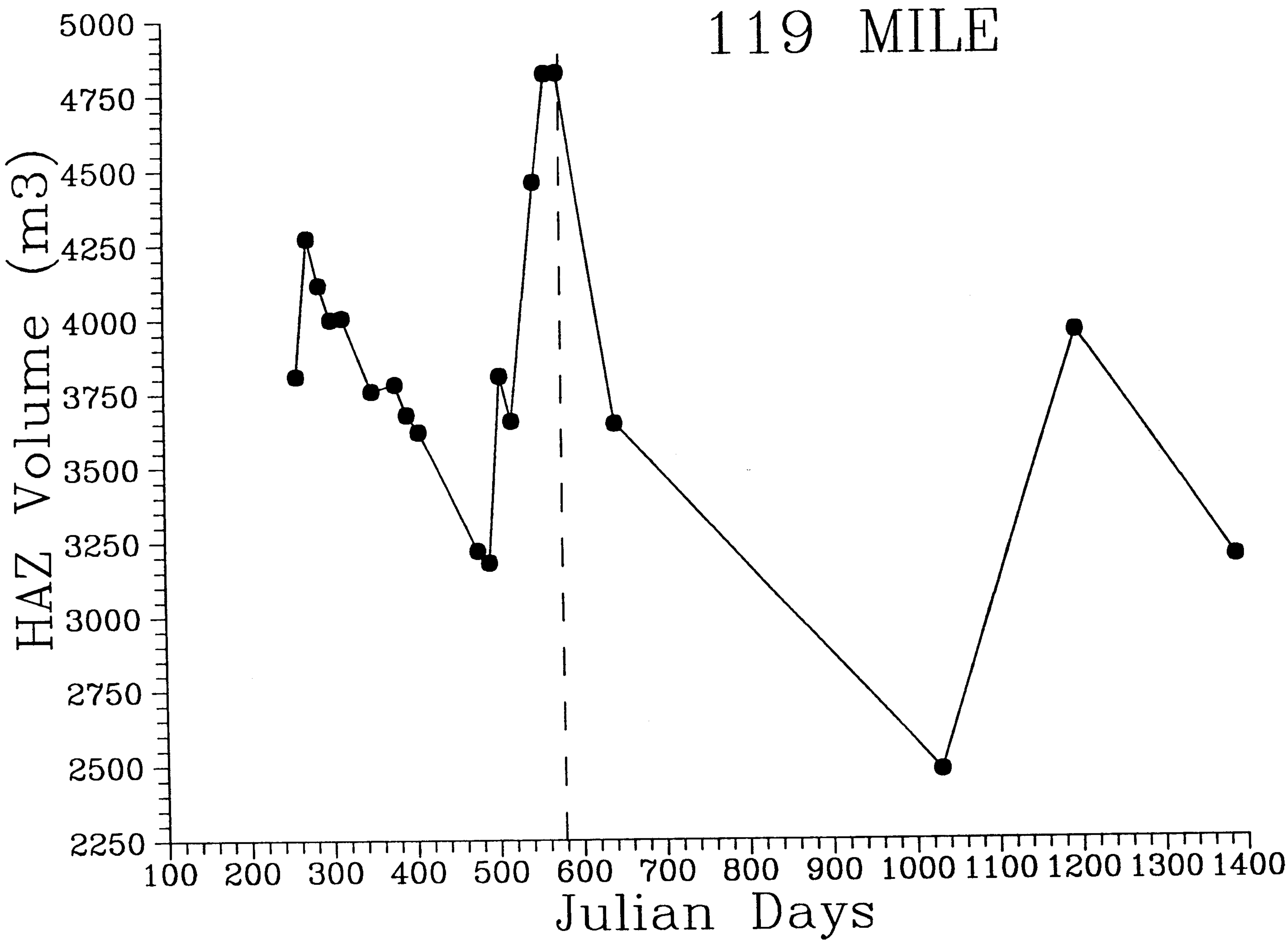
119 MILE PROFILE 1
850 M³/S
142 M³/S
10-26-92
04-10-93
10-18-93
Elevation (m)
Distance (m)
98
96
94
92
90
88
86
84
82
90
100
110
120
130
140
150
160
170
180
190


119 MILE PROFILE 3
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
98
96
94
92
90
88
86
84
82
90
100
110
120
130
140
150
160
170
180
190
10-26-92
04-10-93
10-18-93

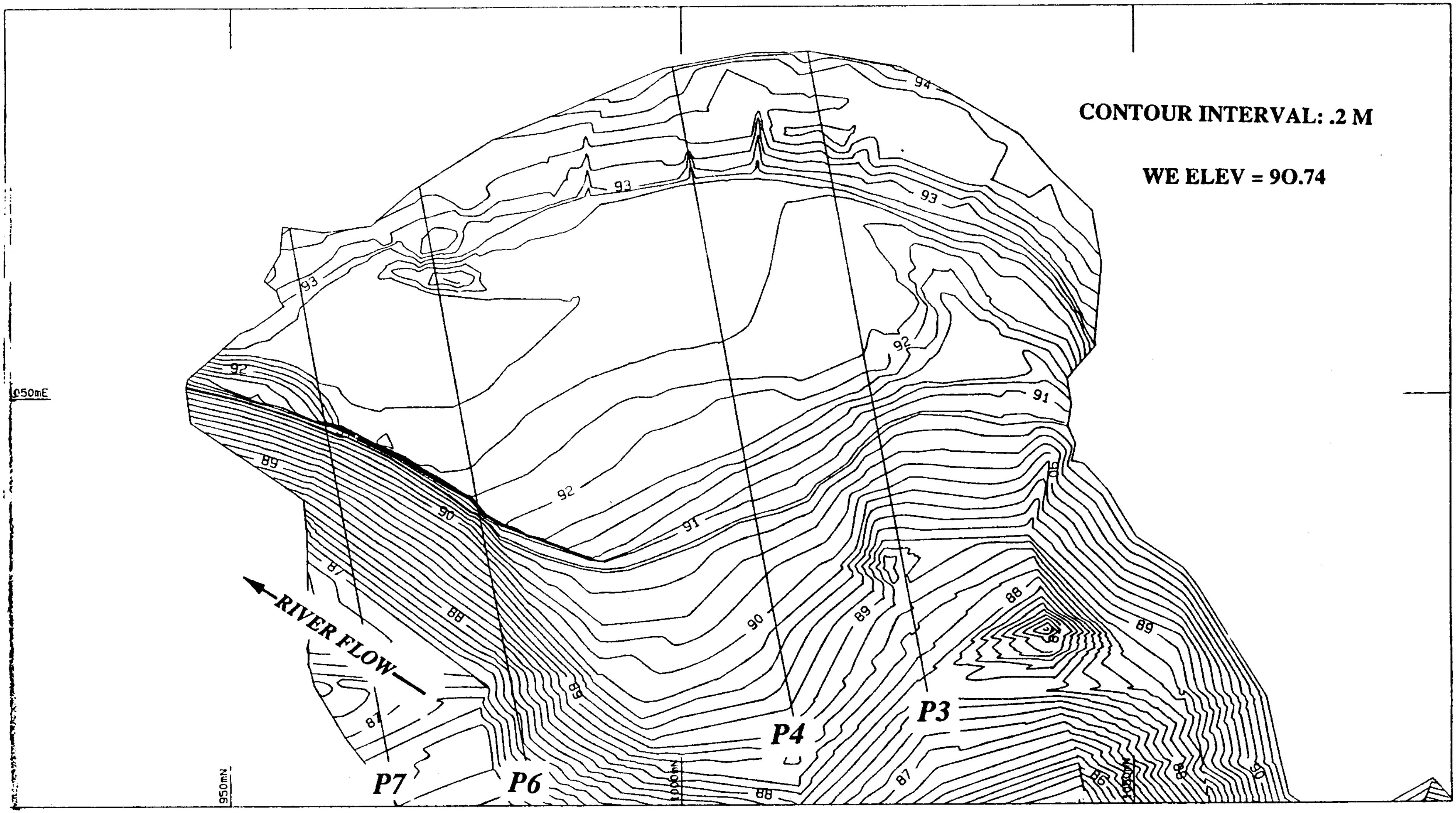

119 MILE PROFILE 4
850 M³/S
142 M³/S
10-26-92
04-10-93
10-18-93
Elevation (m)
Distance (m)
98
96
94
92
90
88
86
84
82
90
100
110
120
130
140
150
160
170
180
190



119 MILE PROFILE 5
850 M³/S
142 M³/S
10-26-92
04-10-93
10-18-93
Elevation (m)
Distance (m)
98
96
94
92
90
88
86
84
82
90
100
110
120
130
140
150
160
170
180
190


119 MILE
HAZ Volume (m3)
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
2250
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

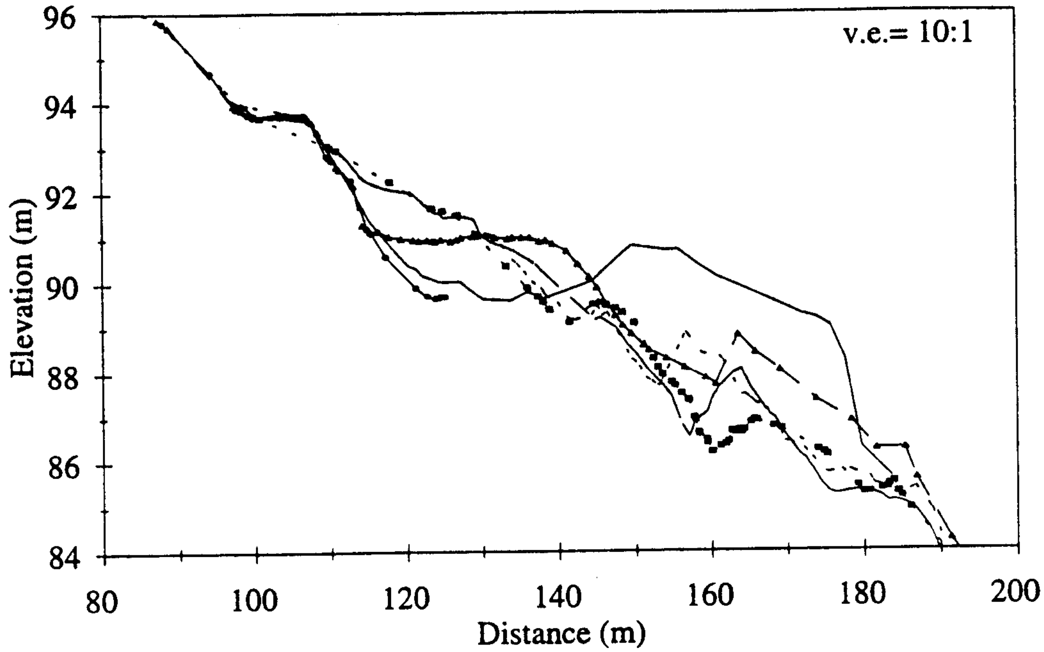
122
5-30-9
Area of Study
RM 122.0



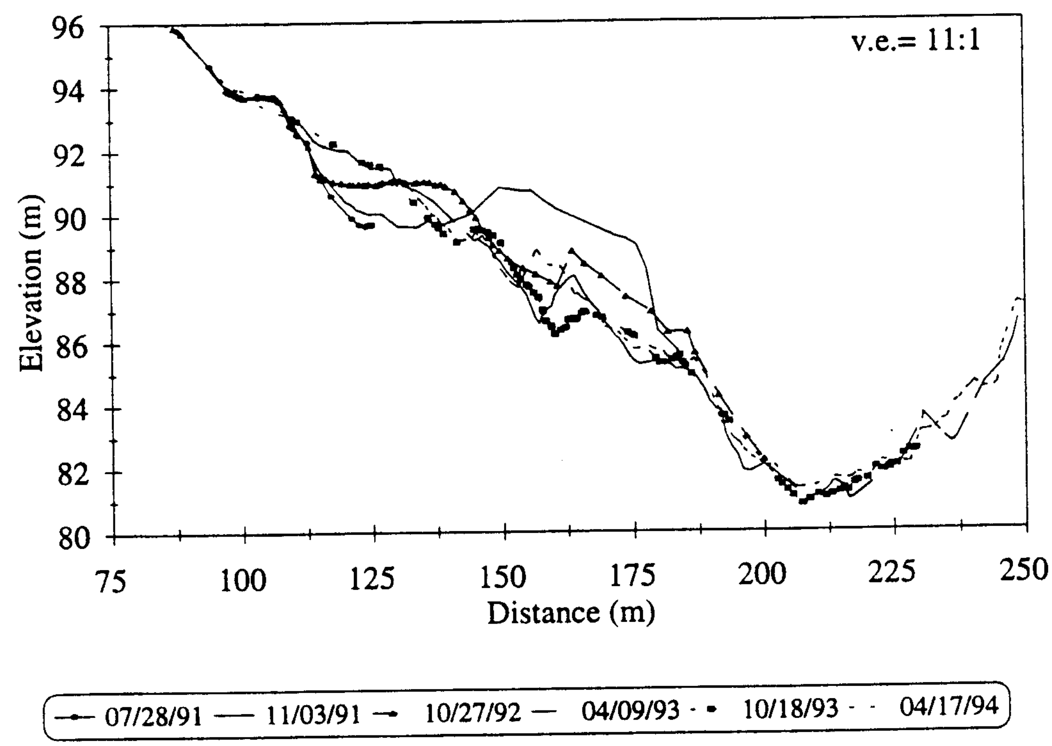
GCES BEACH SURVEY 22Z 122 profiles 122 MILE 4-09-93 1: 400

122 Mile

Near-shore P2

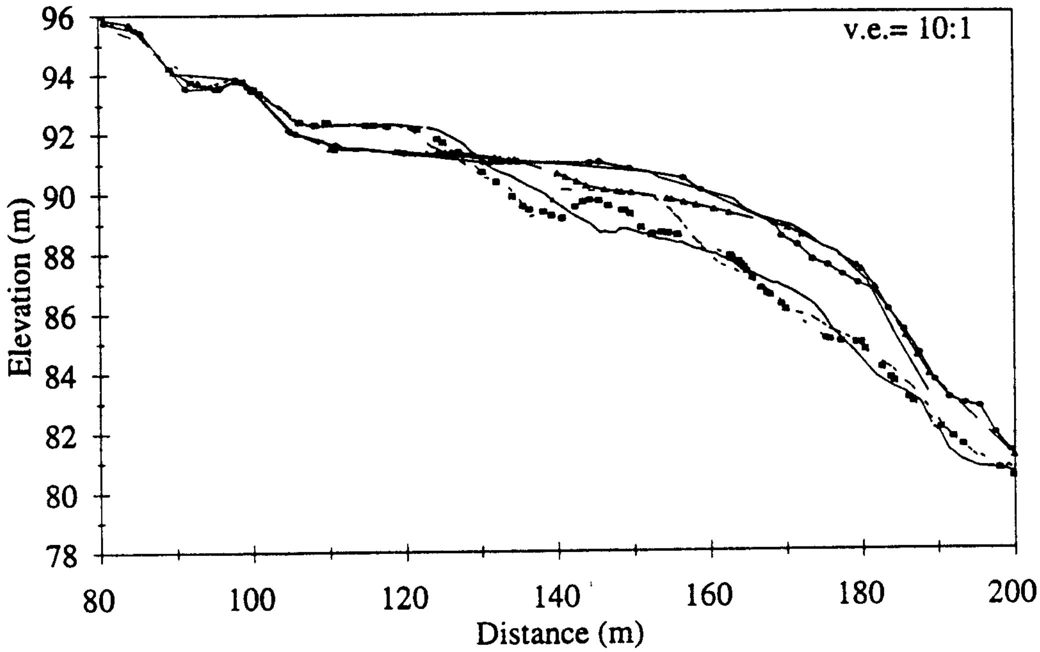


Cross-Channel P2

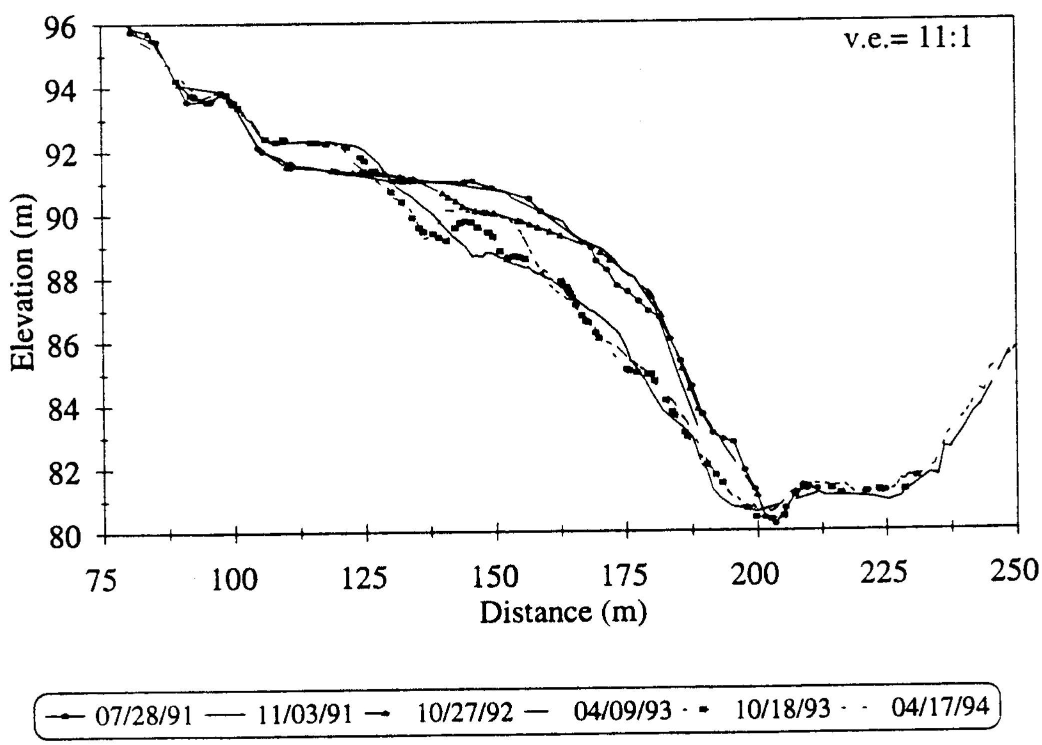


122 Mile

Near-shore P3

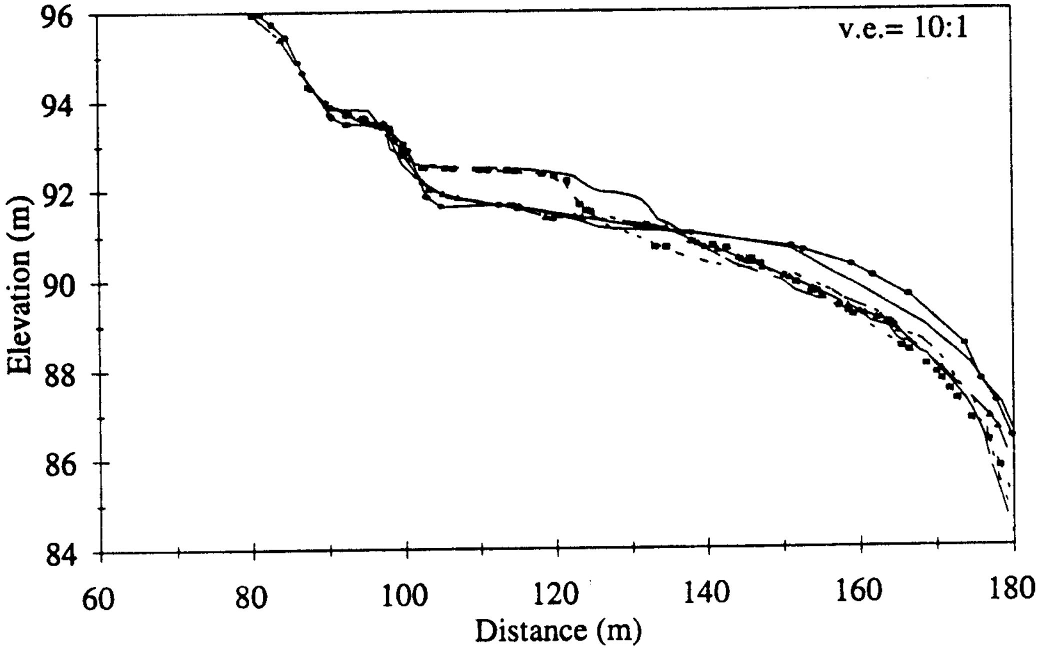


Cross-Channel P3

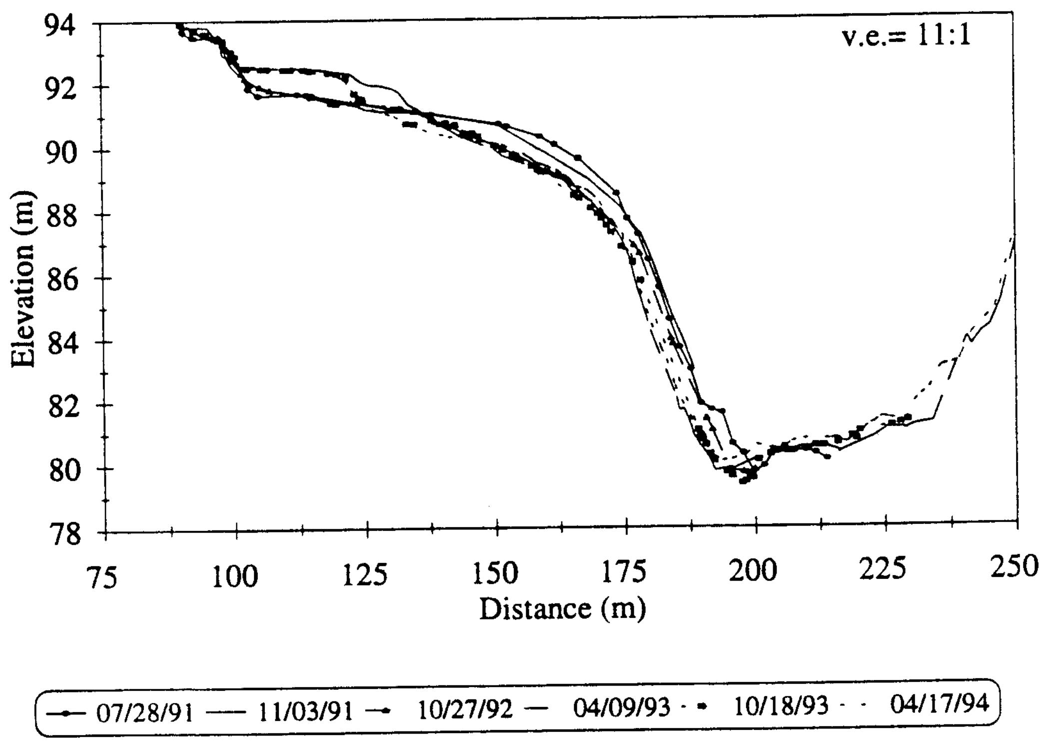


122 Mile

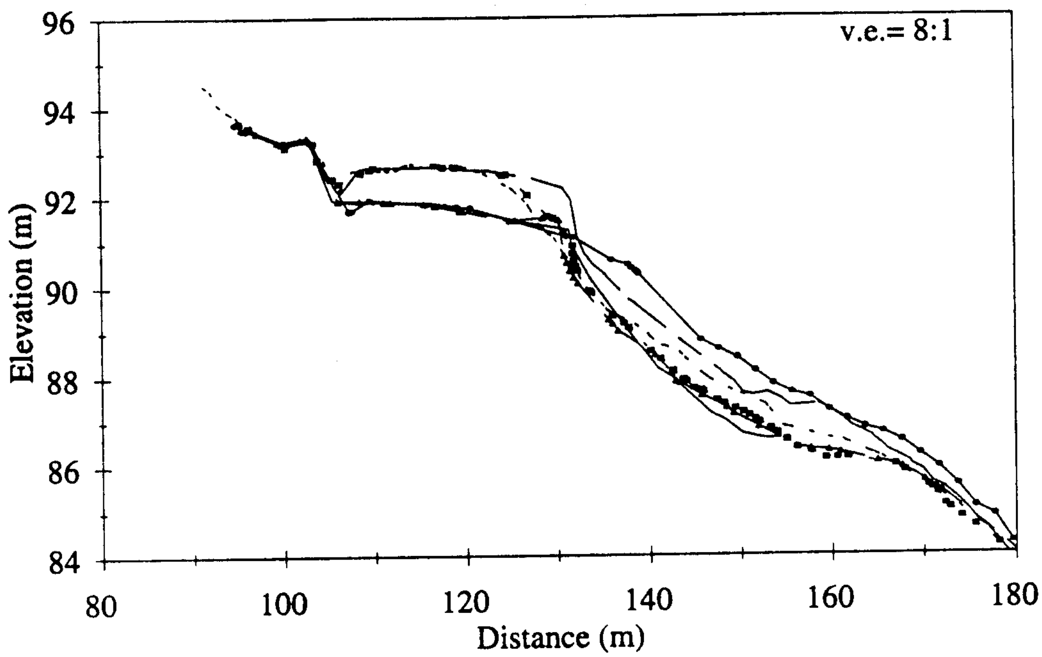
Near-shore P4



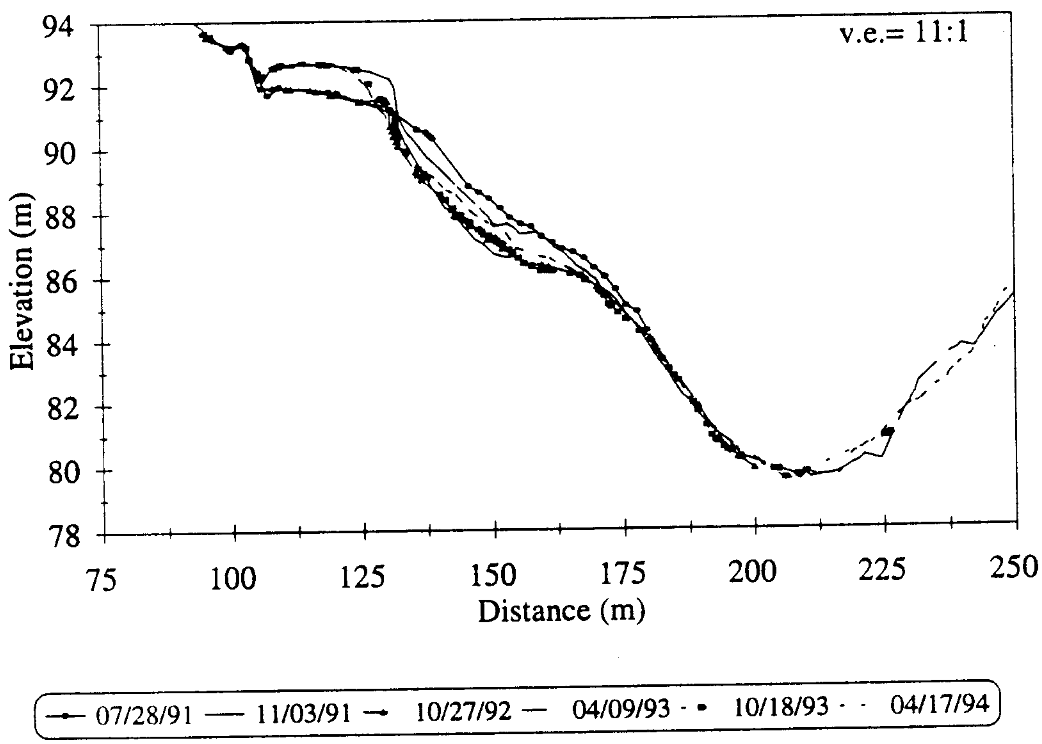
Cross-Channel P4



122 Mile



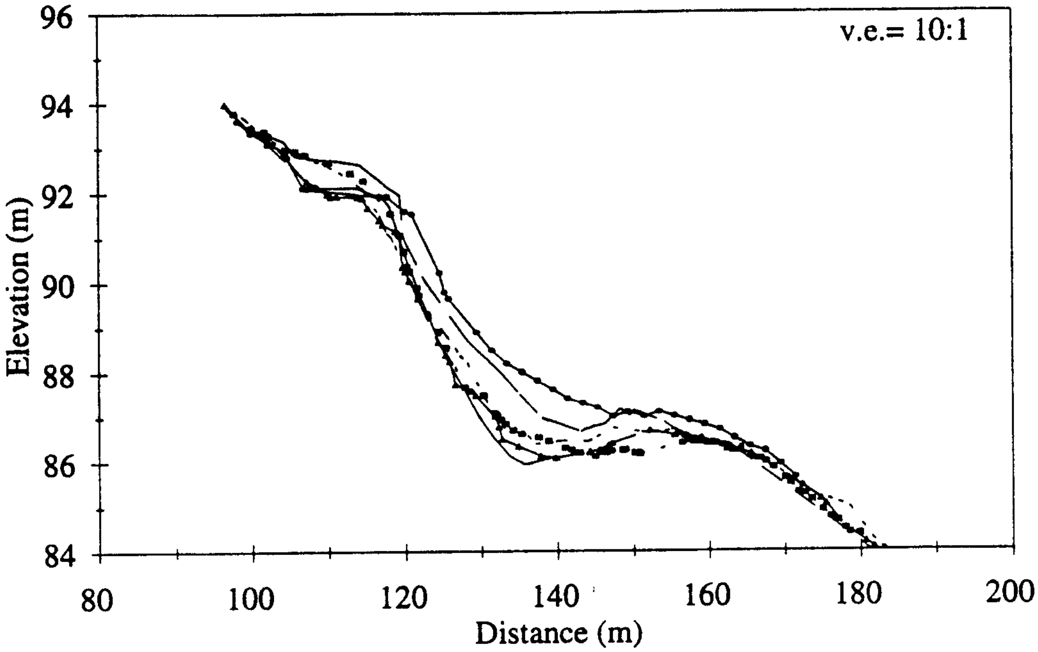
Near-shore P6
v.e.= 8:1
Elevation (m)
Distance (m)
96
94
92
90
88
86
84
80
100
120
140
160
180



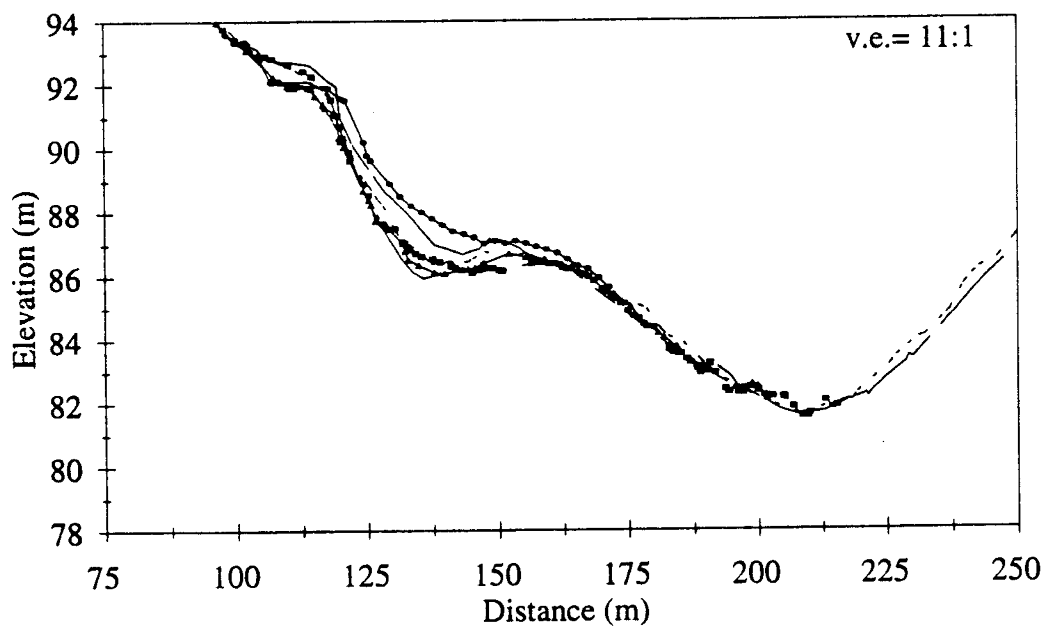
Cross-Channel P6
v.e.= 11:1
Elevation (m)
Distance (m)
94
92
90
88
86
84
82
80
78
75
100
125
150
175
200
225
250
07/28/91
11/03/91
10/27/92
04/09/93
10/18/93
04/17/94

122 Mile

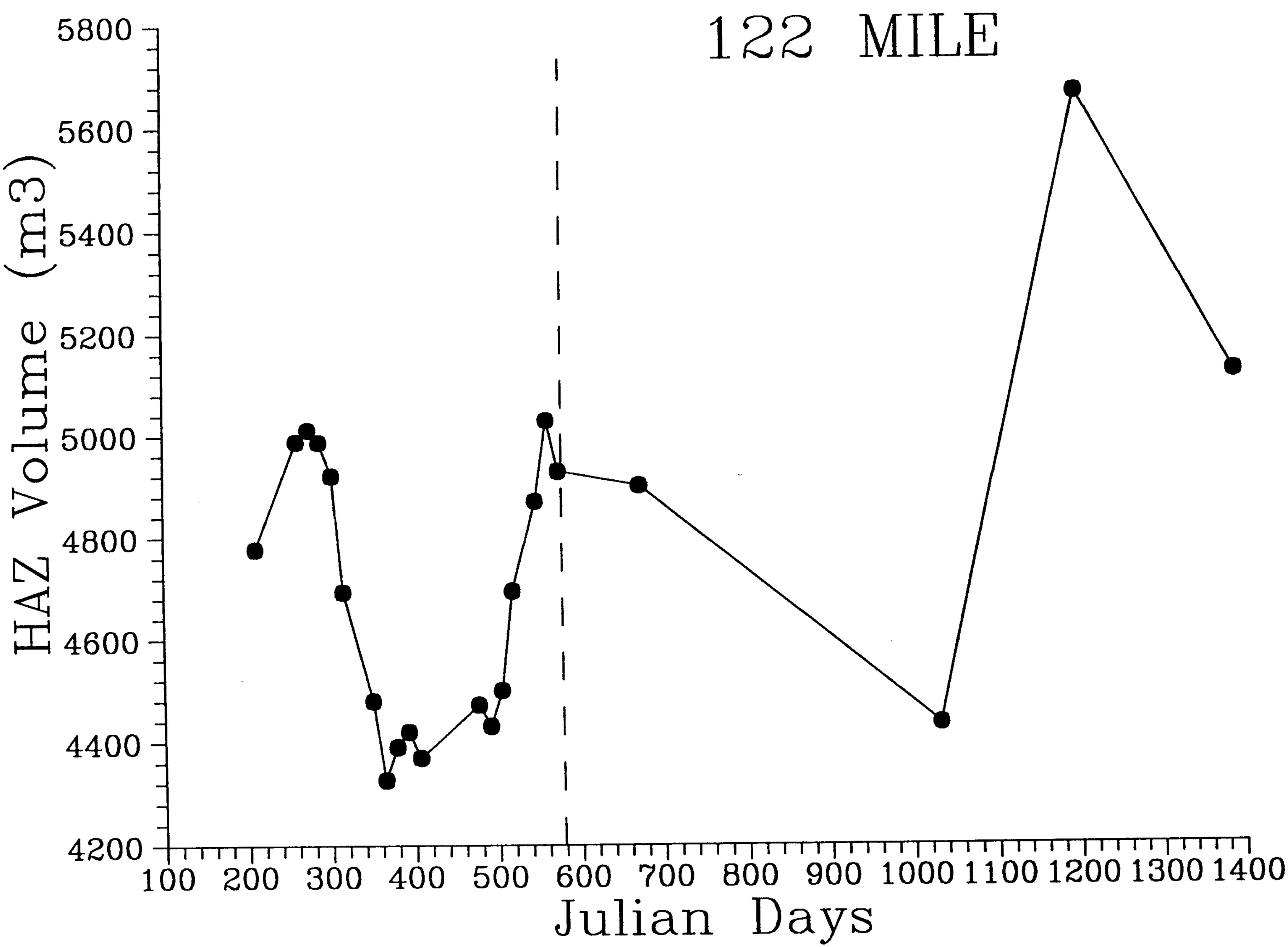
Near-shore P7



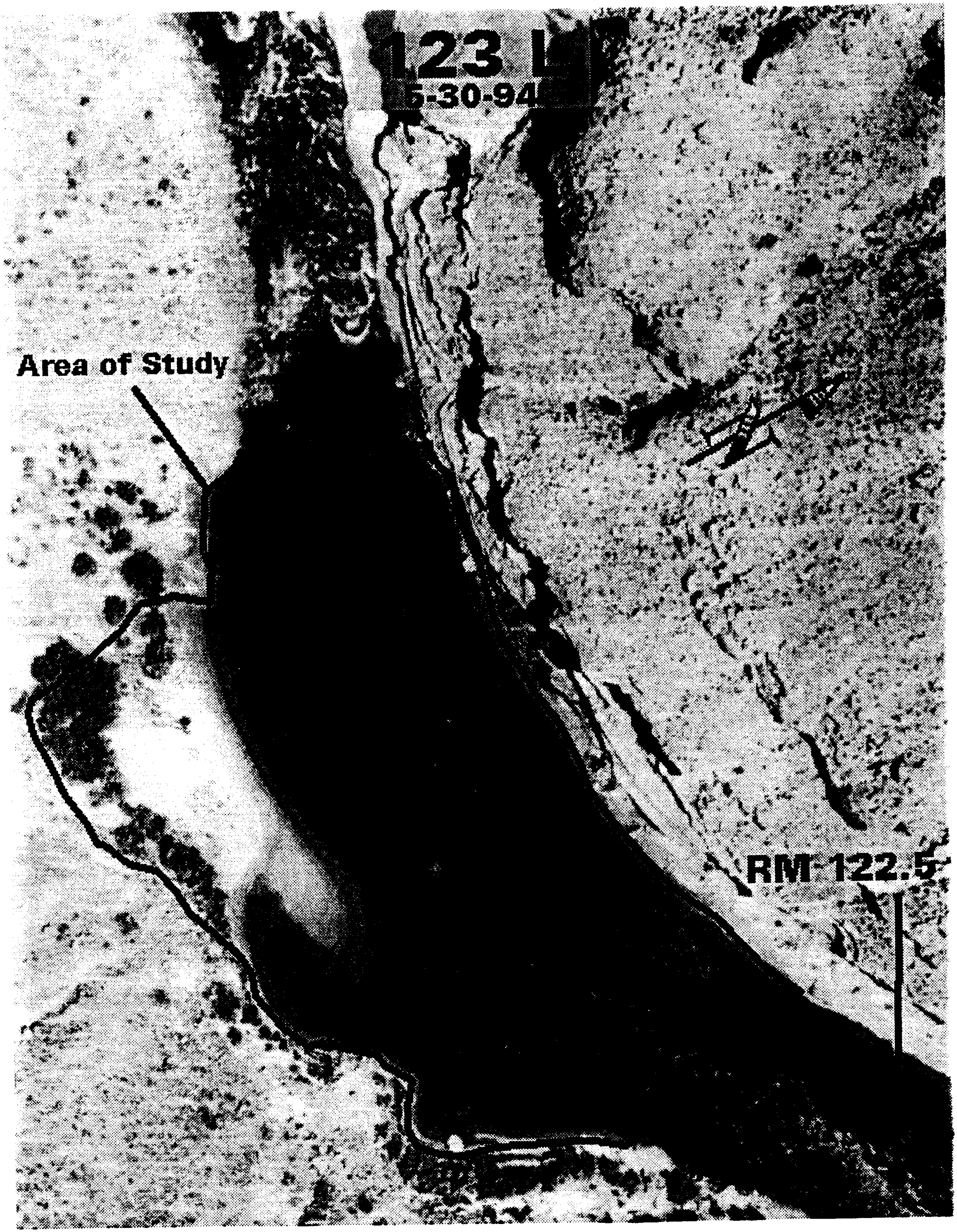
Cross-Channel P7

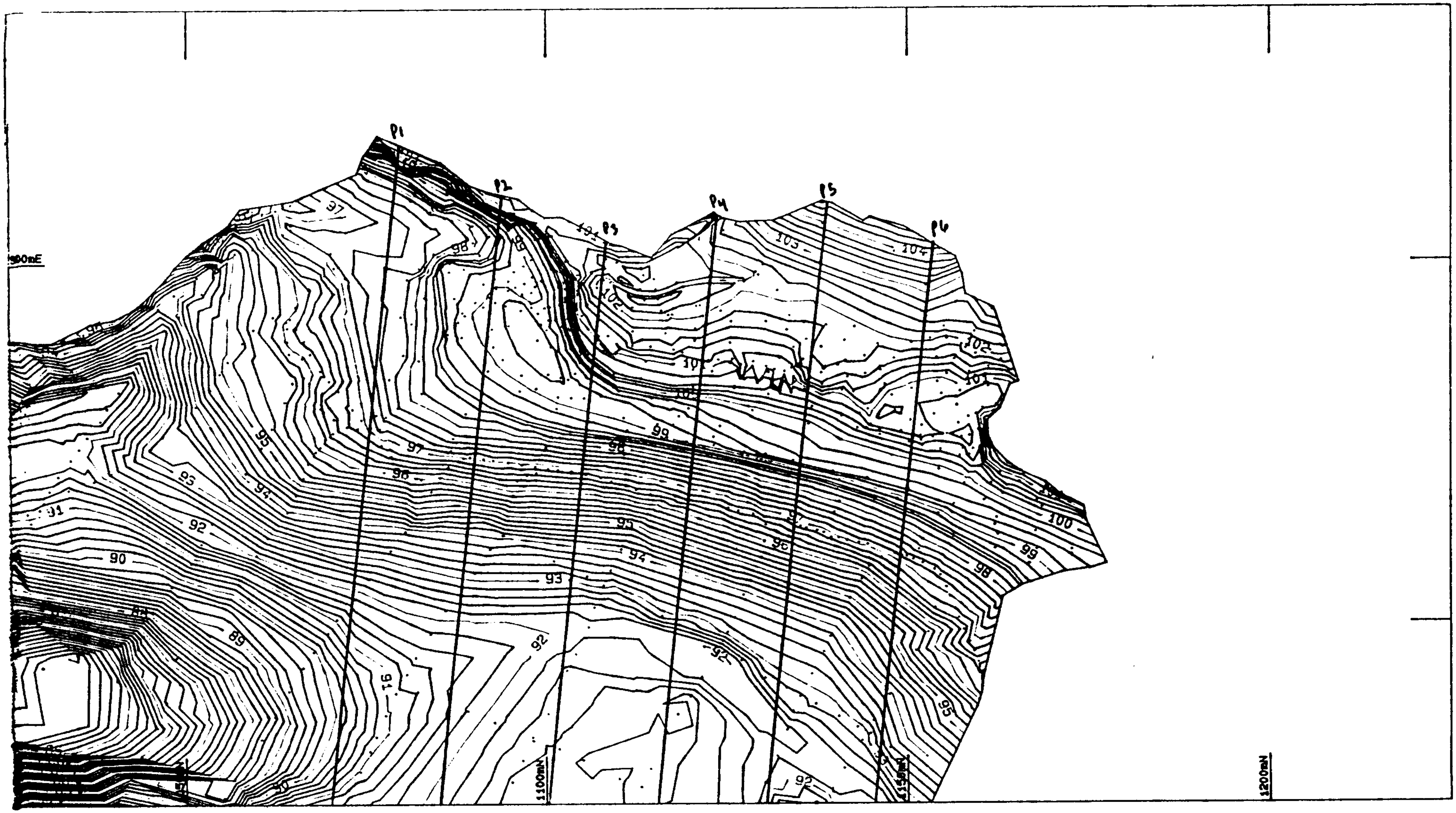


07/28/91 — 11/03/91 — 10/27/92 — 04/09/93 — 10/18/93 — 04/17/94



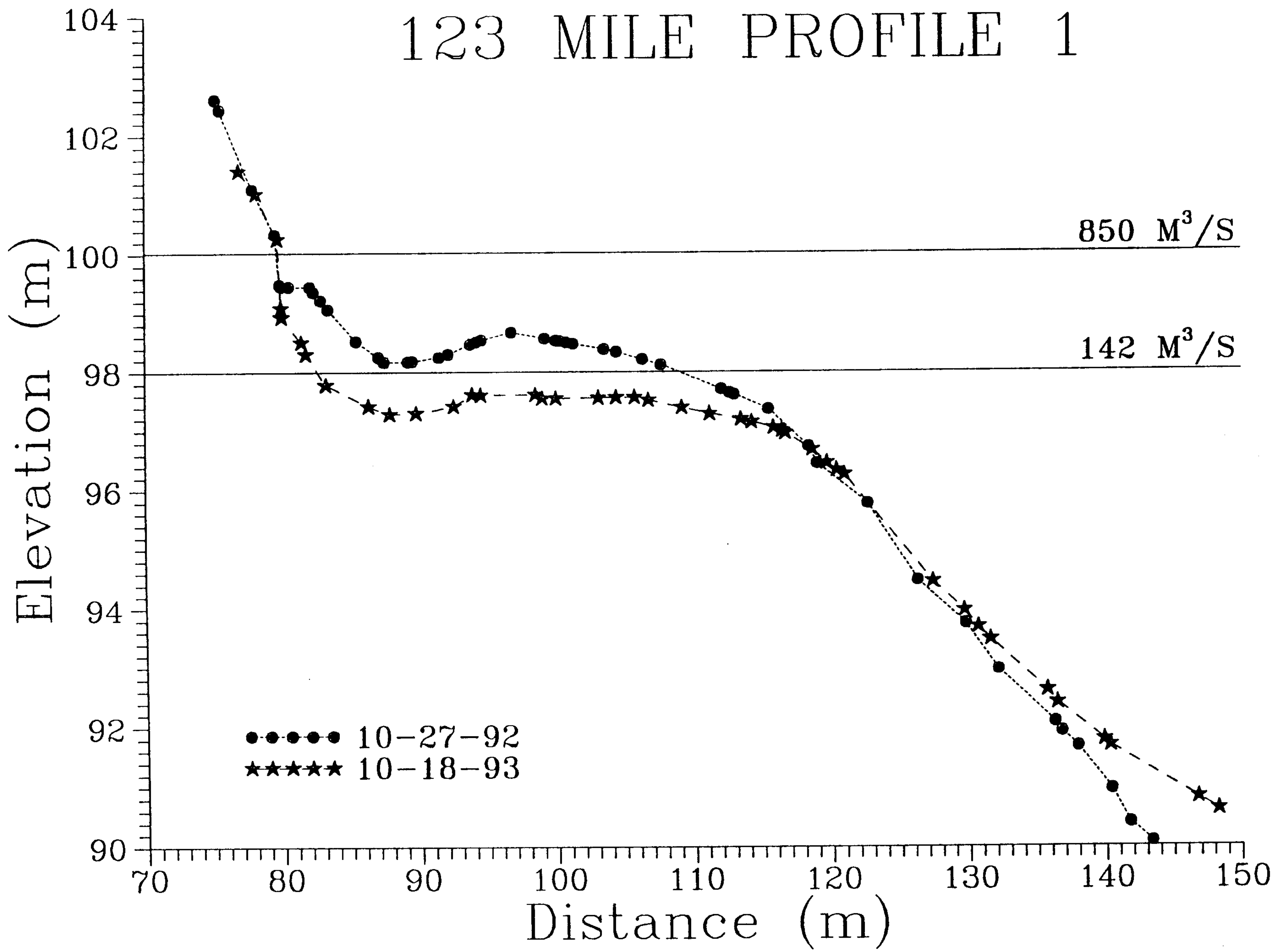
122 MILE
HAZ Volume (m3)
5800
5600
5400
5200
5000
4800
4600
4400
4200
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days


123 L
5-30-94
Area of Study
RM 122.5

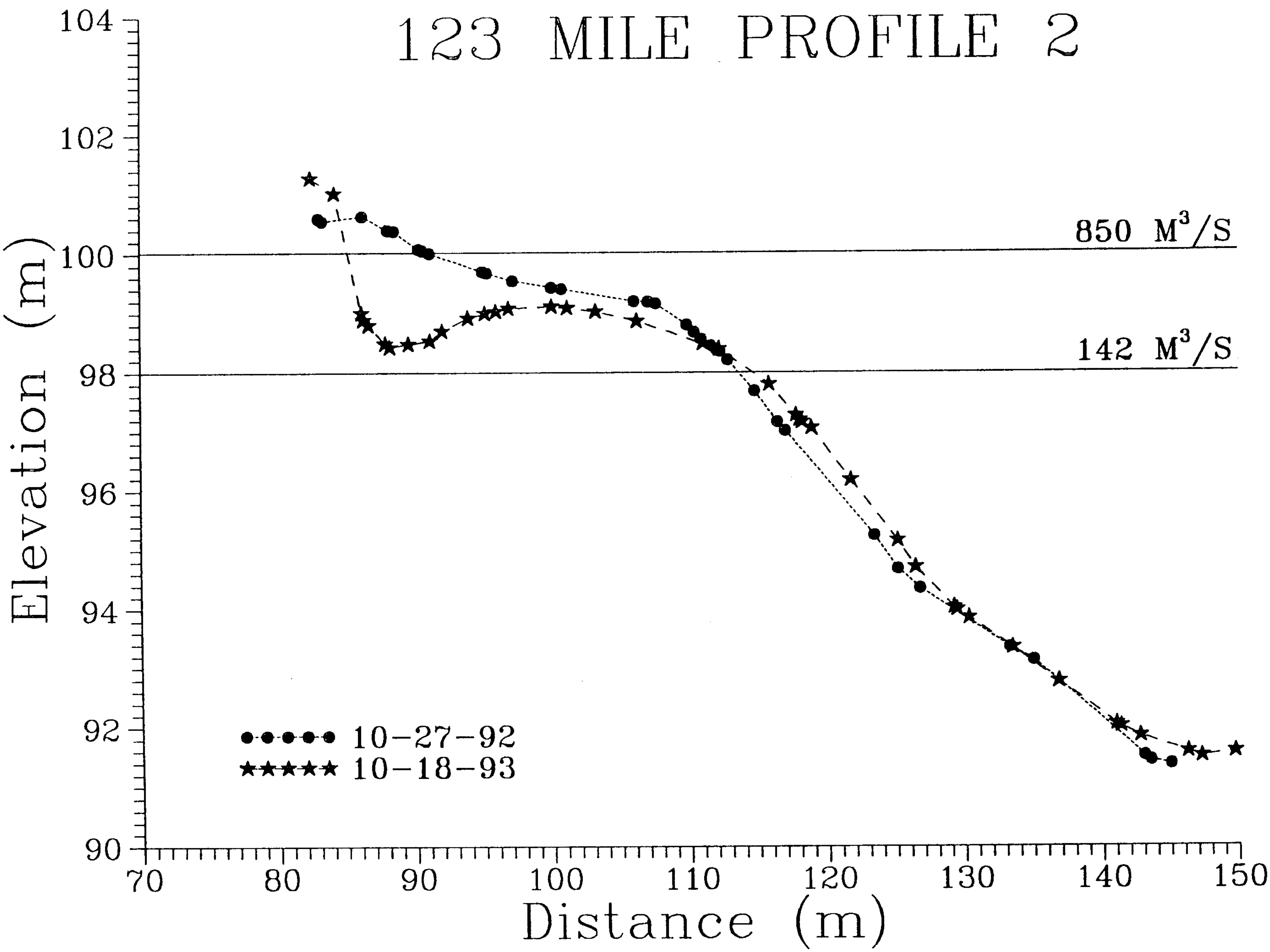


123L-B23

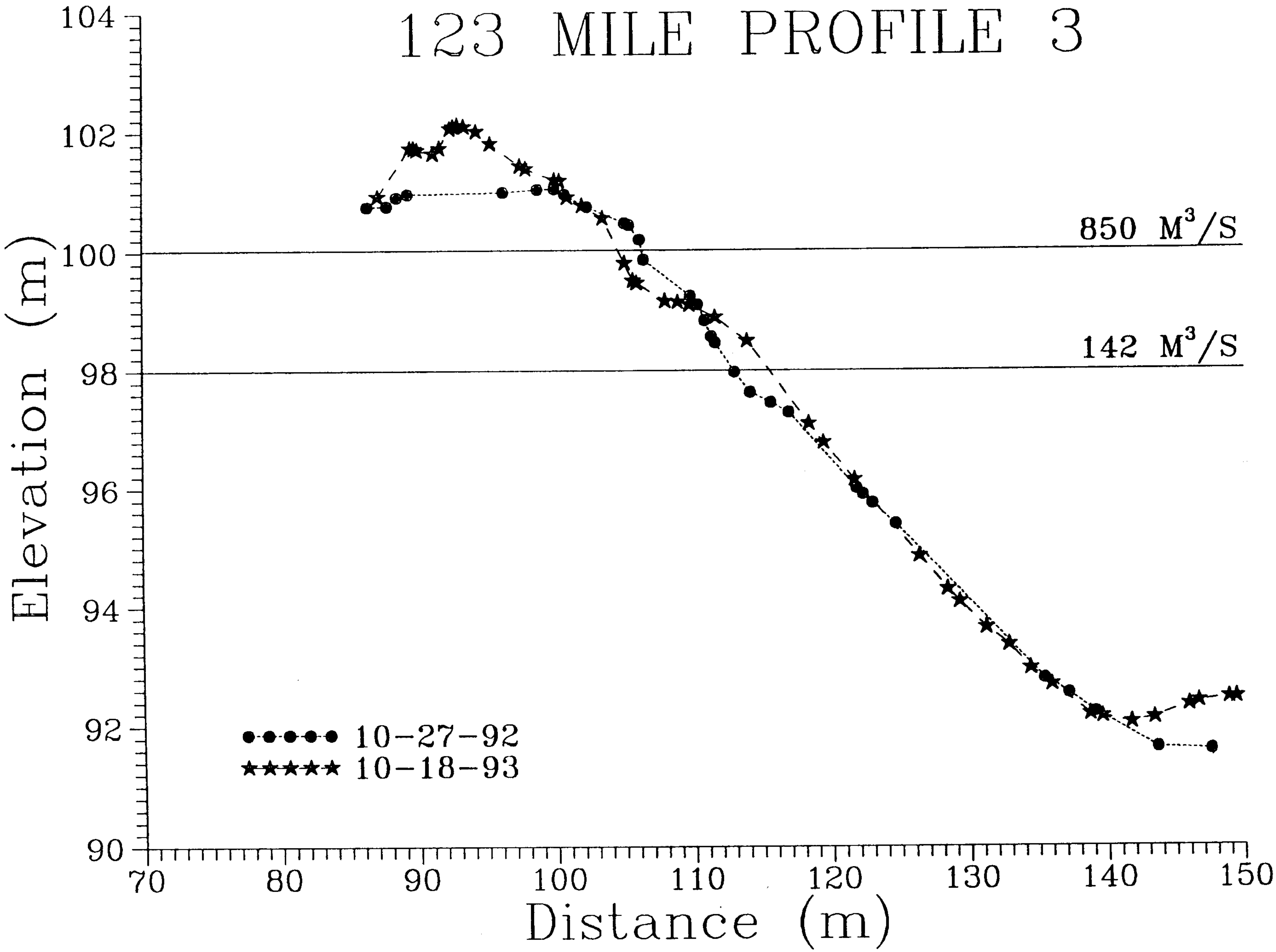
GCES BEACH SURVEY B23 123 MILE 10-18-93 1: 500

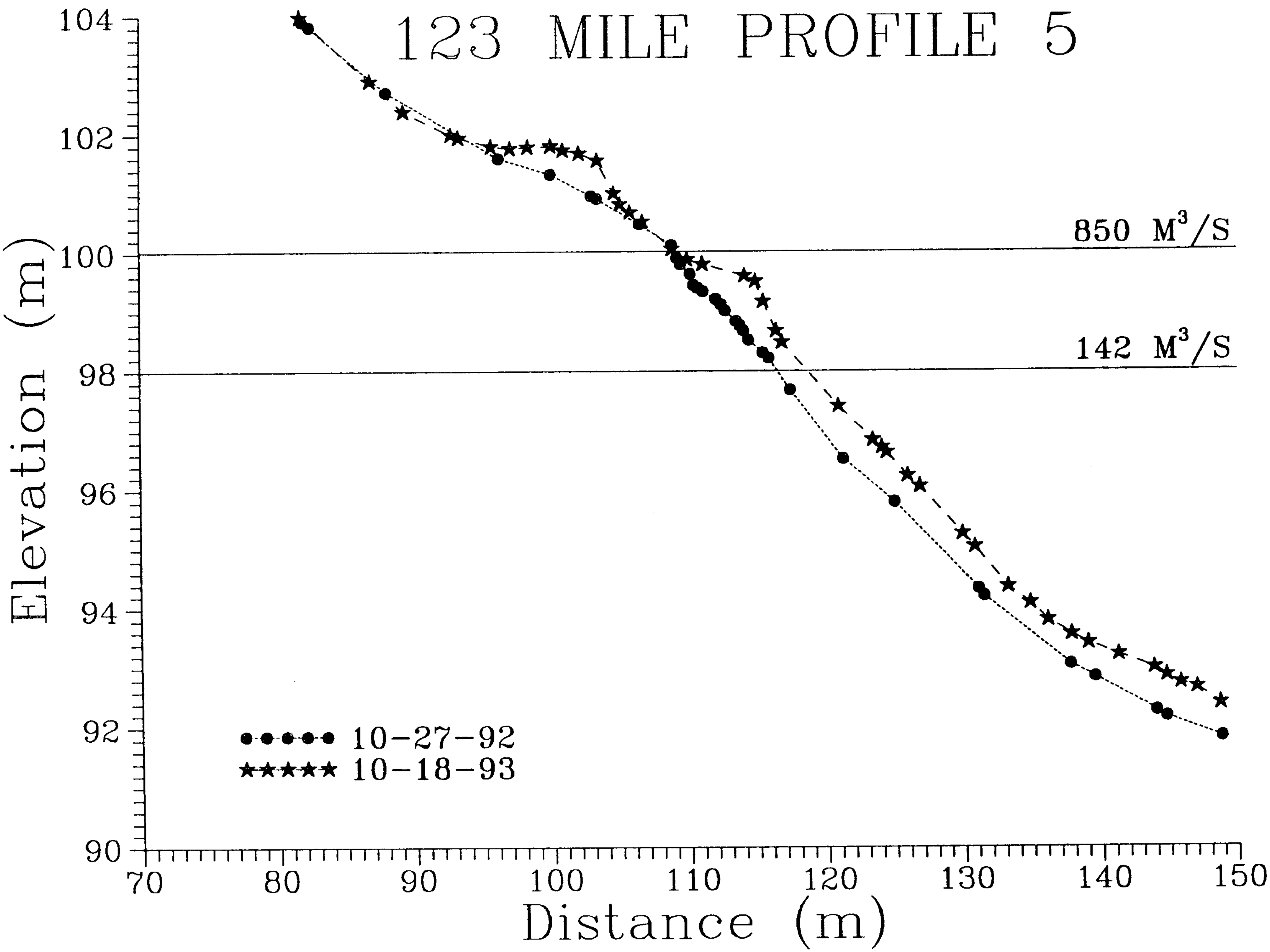


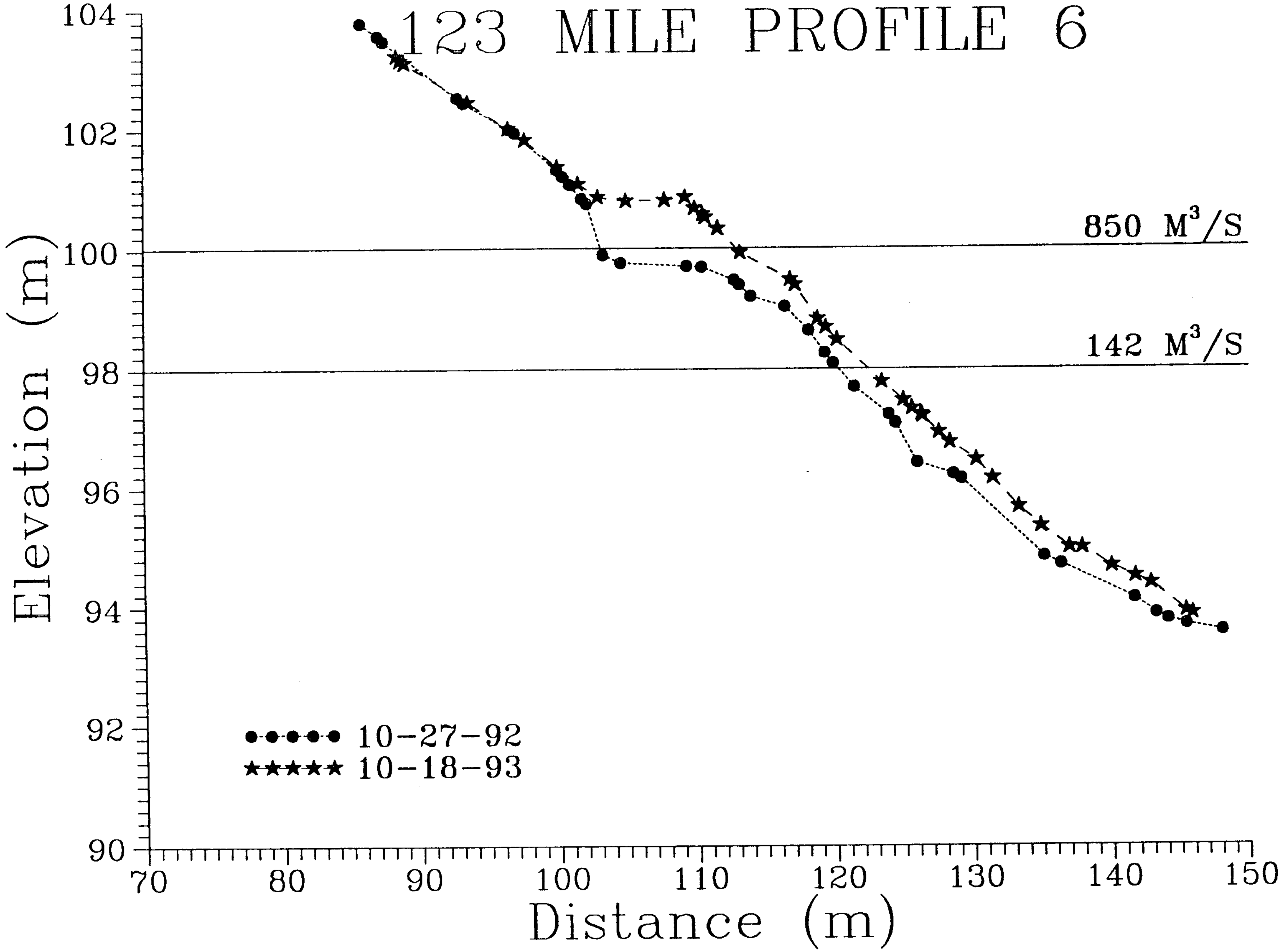
123 MILE PROFILE 1
850 M³/S
142 M³/S
10-27-92
10-18-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
70
80
90
100
110
120
130
140
150



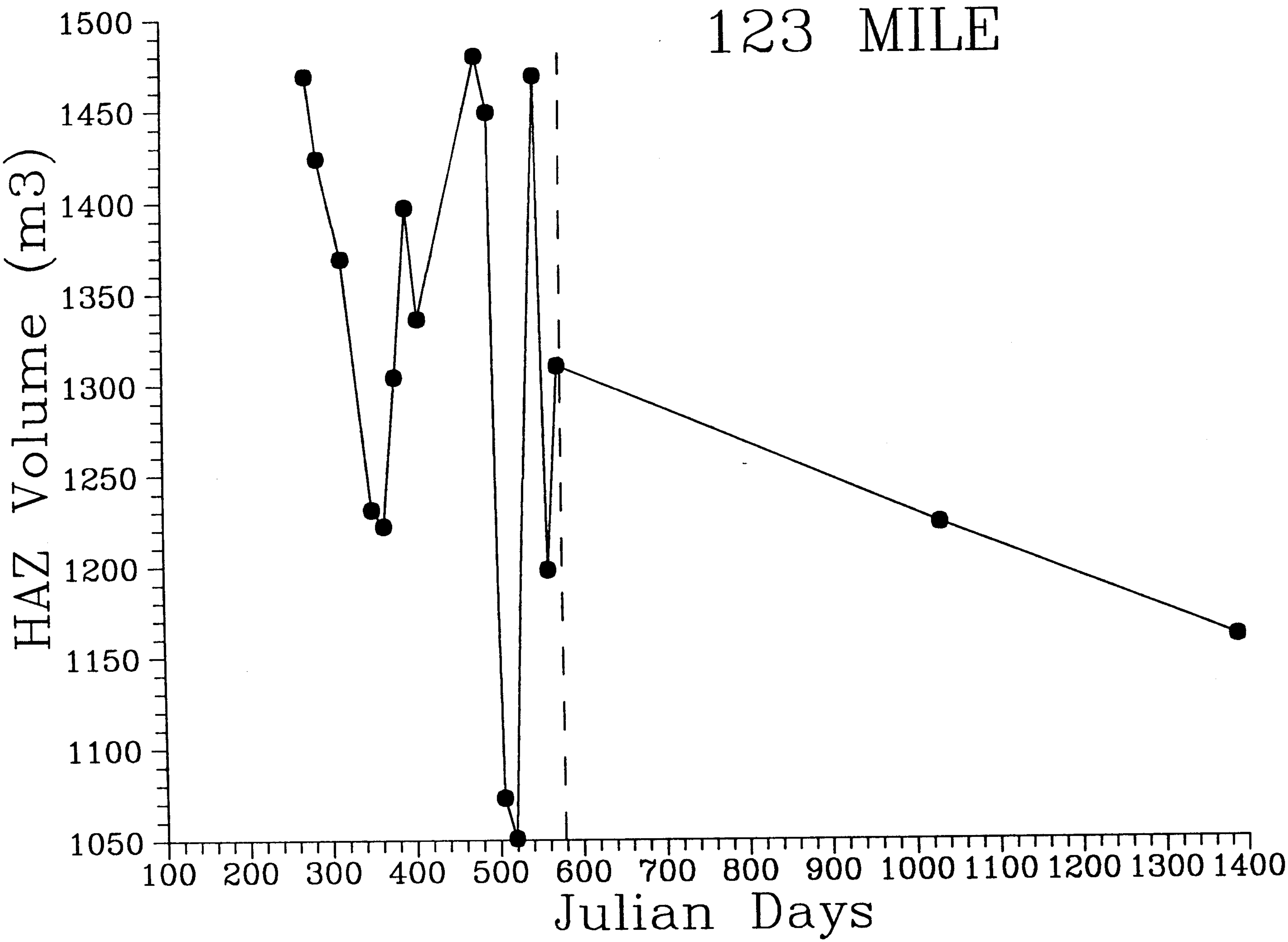
123 MILE PROFILE 2
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
10-27-92
10-18-93
104
102
100
98
96
94
92
90
70
80
90
100
110
120
130
140
150


123 MILE PROFILE 3
850 M³/S
142 M³/S
10-27-92
10-18-93
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
70
80
90
100
110
120
130
140
150

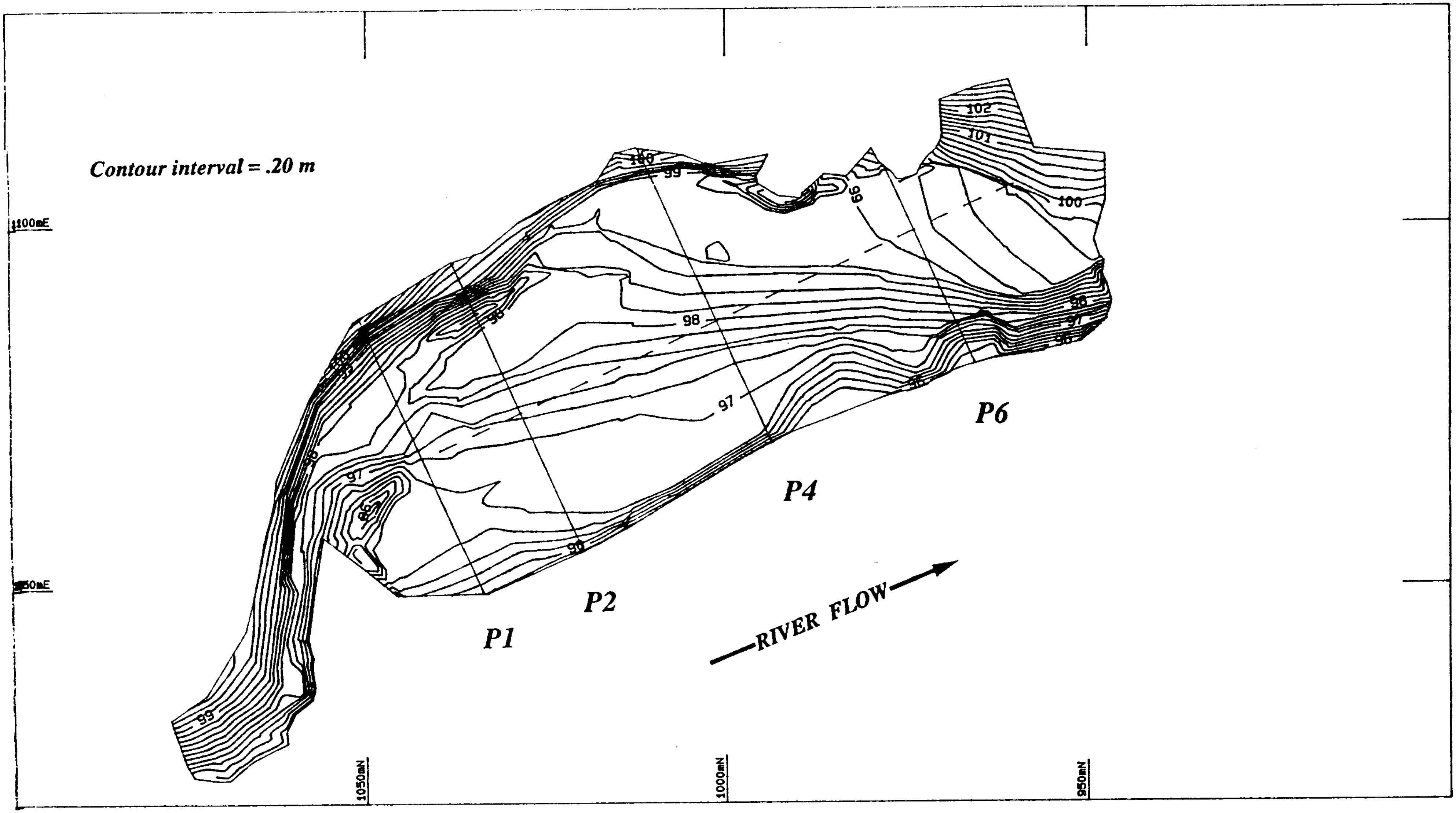

123 MILE PROFILE 5
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
104
102
100
98
96
94
92
90
70
80
90
100
110
120
130
140
150
10-27-92
10-18-93



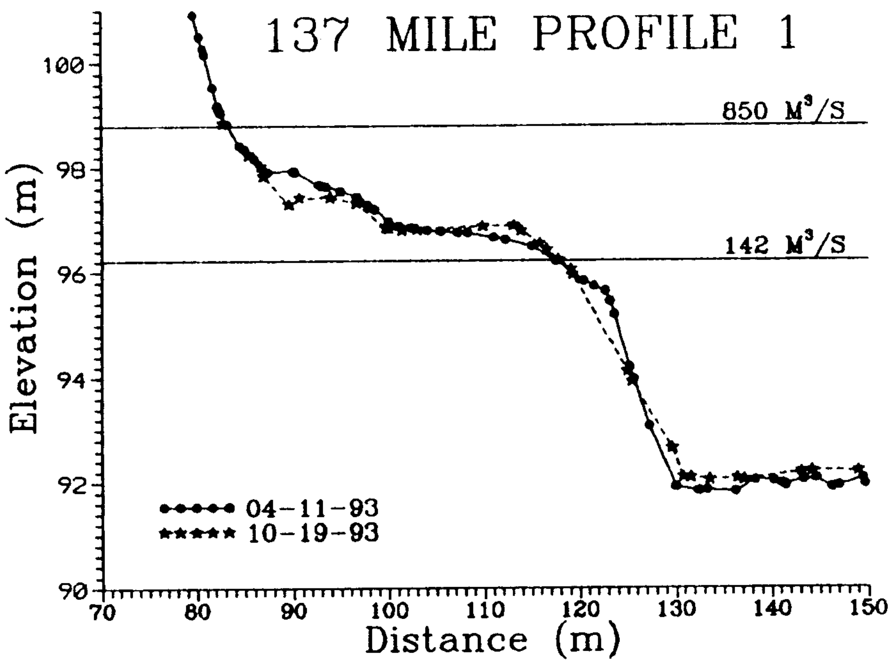
123 MILE PROFILE 6
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
10-27-92
10-18-93
104
102
100
98
96
94
92
90
70
80
90
100
110
120
130
140
150

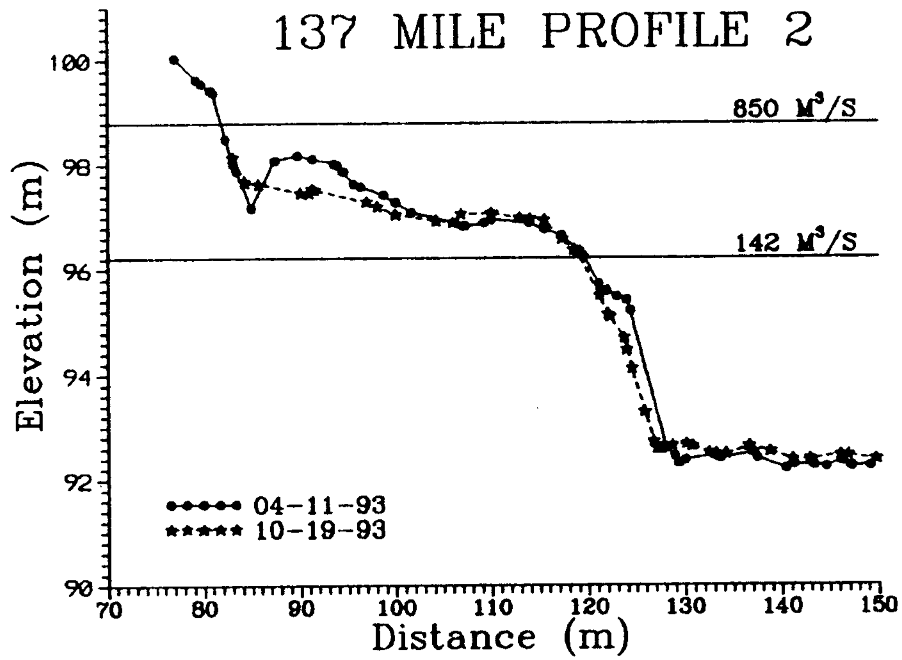

123 MILE
HAZ Volume (m3)
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

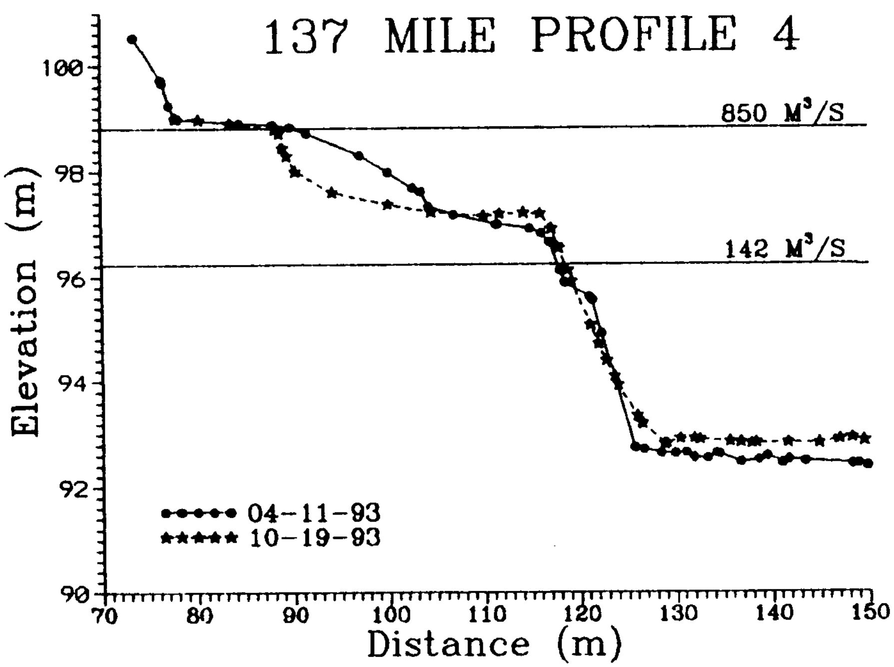

137 L
5-30-94
Area of Study
N
RM 136.5

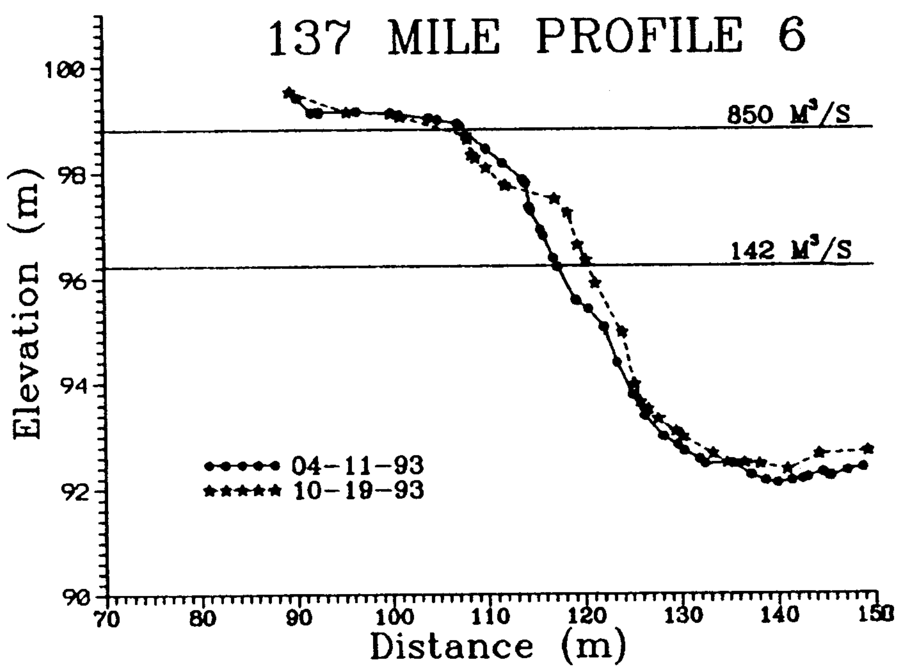


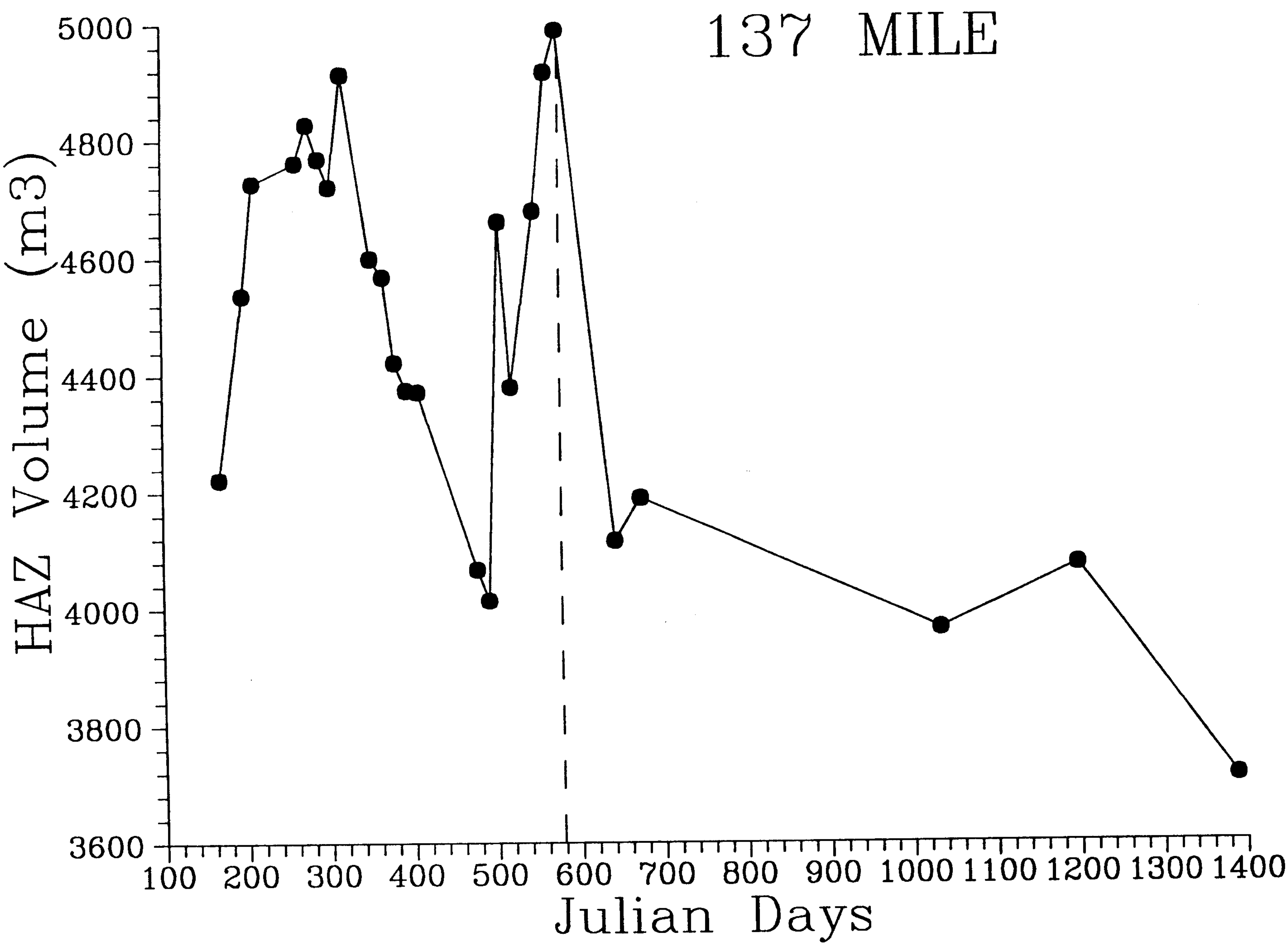
GCES BEACH SURVEY 24Z Quarterly Report 137 MILE 4-11-93 1: 500

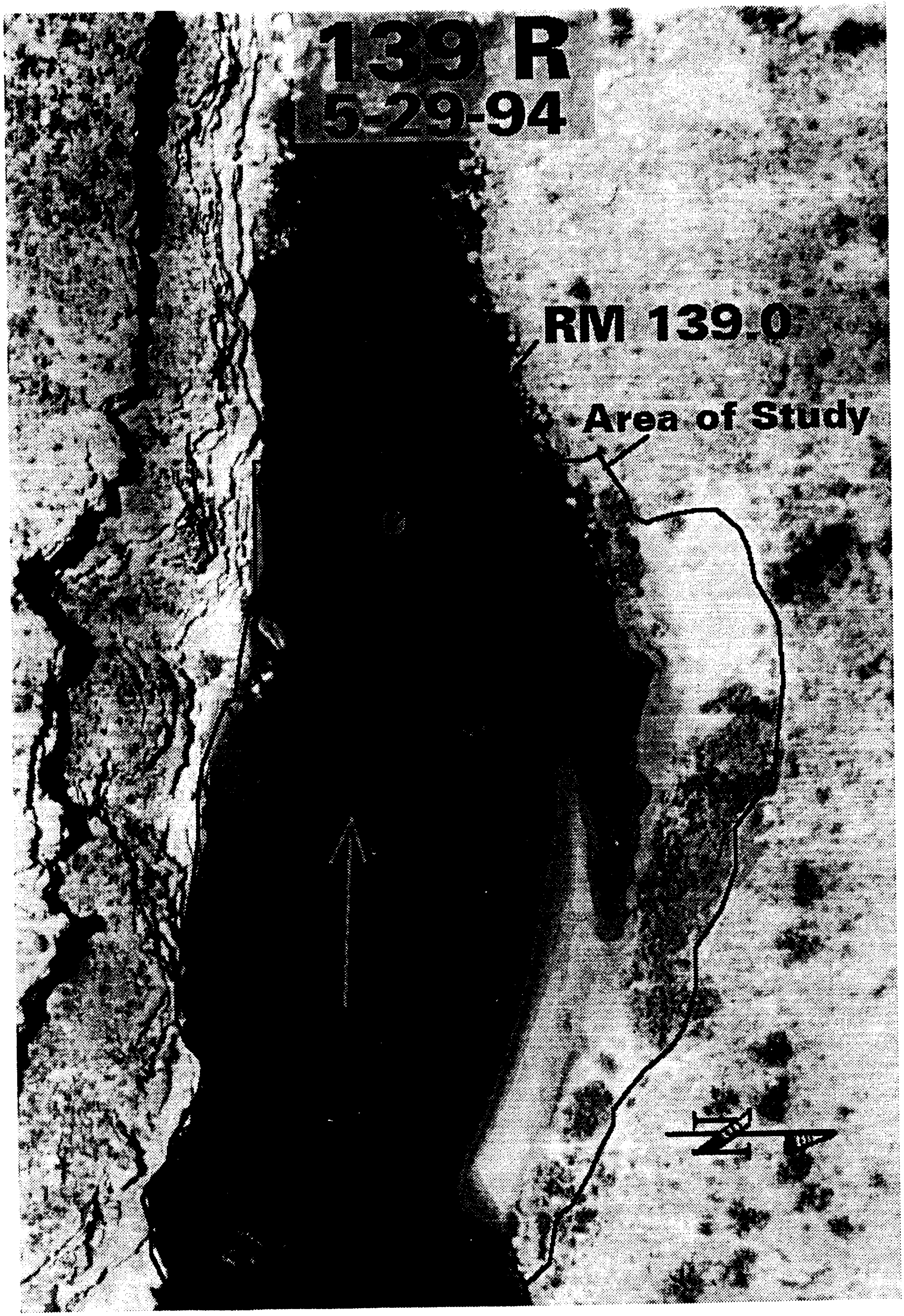

137 MILE PROFILE 1
850 M³/S
142 M³/S
04-11-93
10-19-93
Elevation (m)
Distance (m)

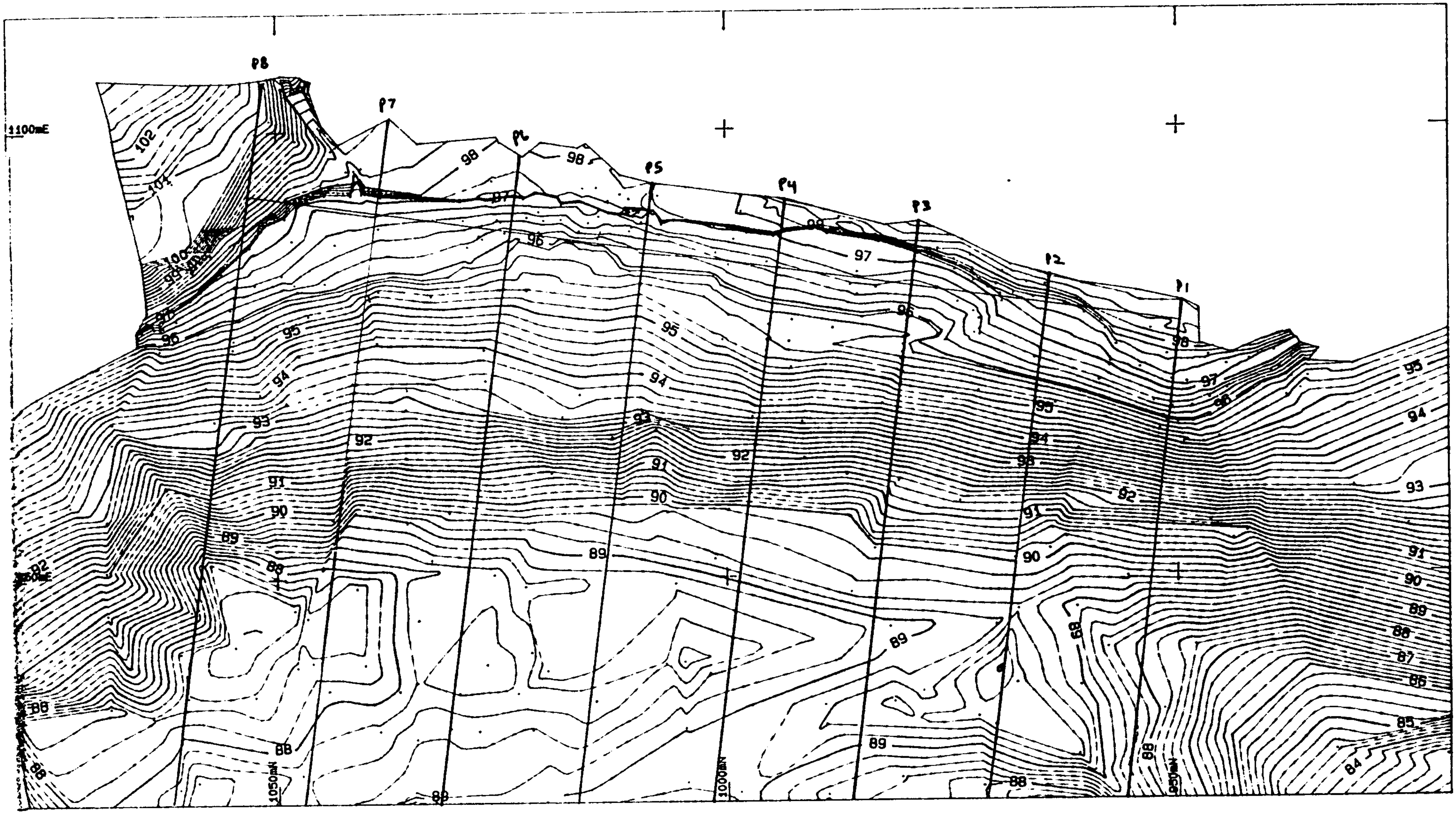

137 MILE PROFILE 2
850 M³/S
142 M³/S
04-11-93
10-19-93
Elevation (m)
Distance (m)


137 MILE PROFILE 4
850 M³/S
142 M³/S
04-11-93
10-19-93
Elevation (m)
Distance (m)


137 MILE PROFILE 6
850 M³/S
142 M³/S
04-11-93
10-19-93
Elevation (m)
Distance (m)


137 MILE
HAZ Volume (m3)
5000
4800
4600
4400
4200
4000
3800
3600
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days


139 R
5-29-94
RM 139.0
Area of Study

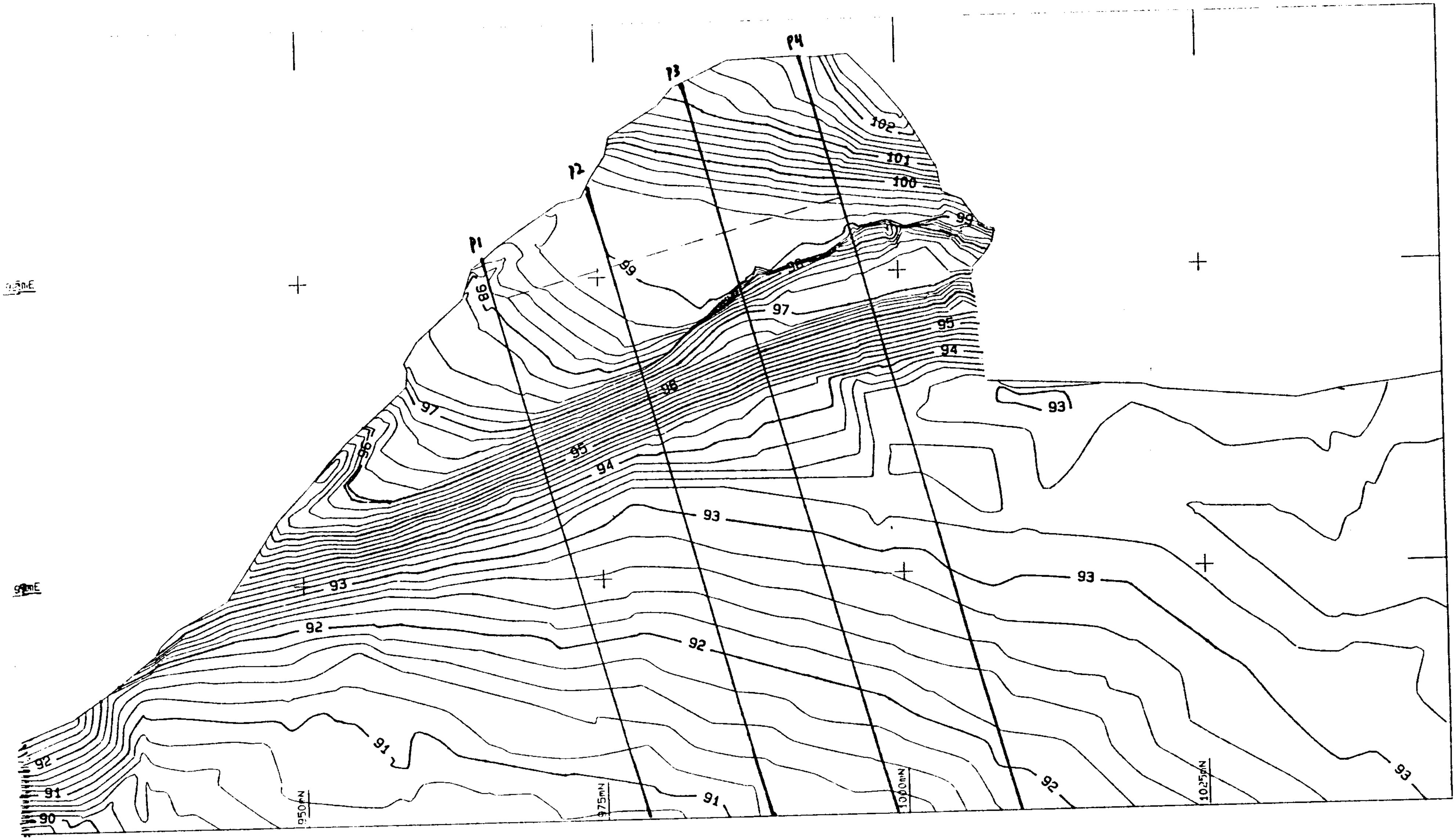


GCES BEACH SURVEY 25Y

139R-25Y

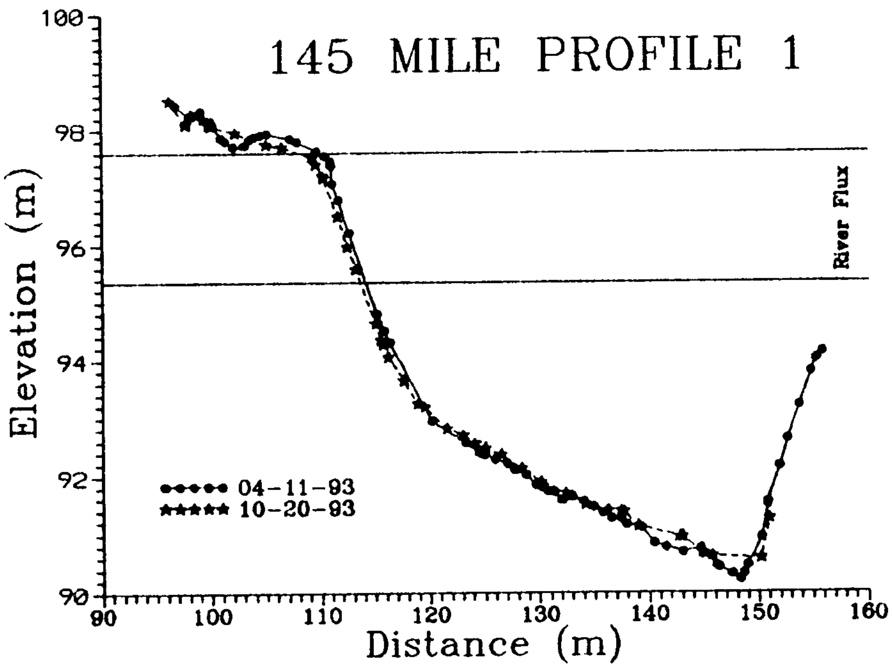
139 MILE 10-28-92

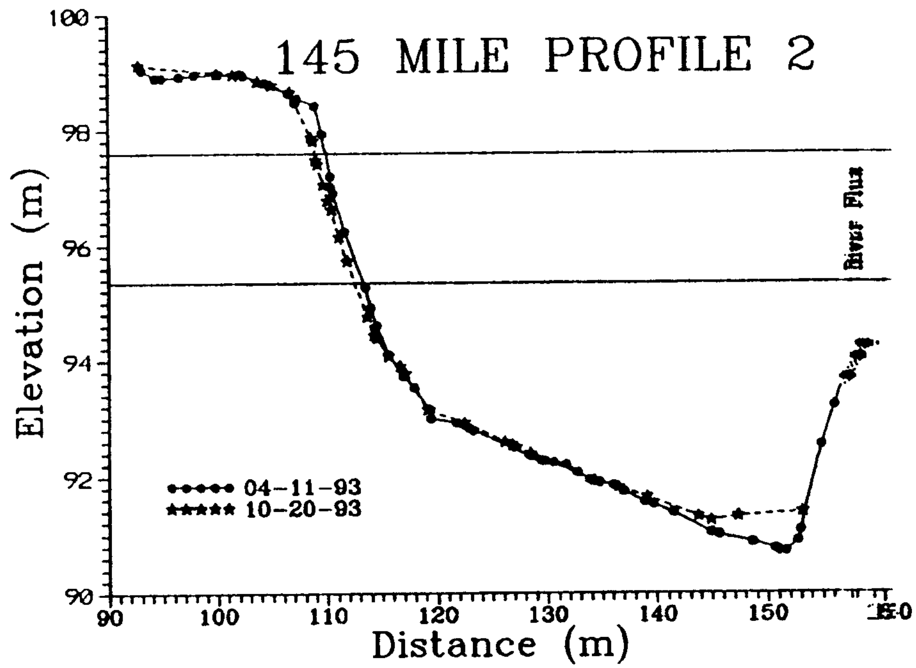
1: 400

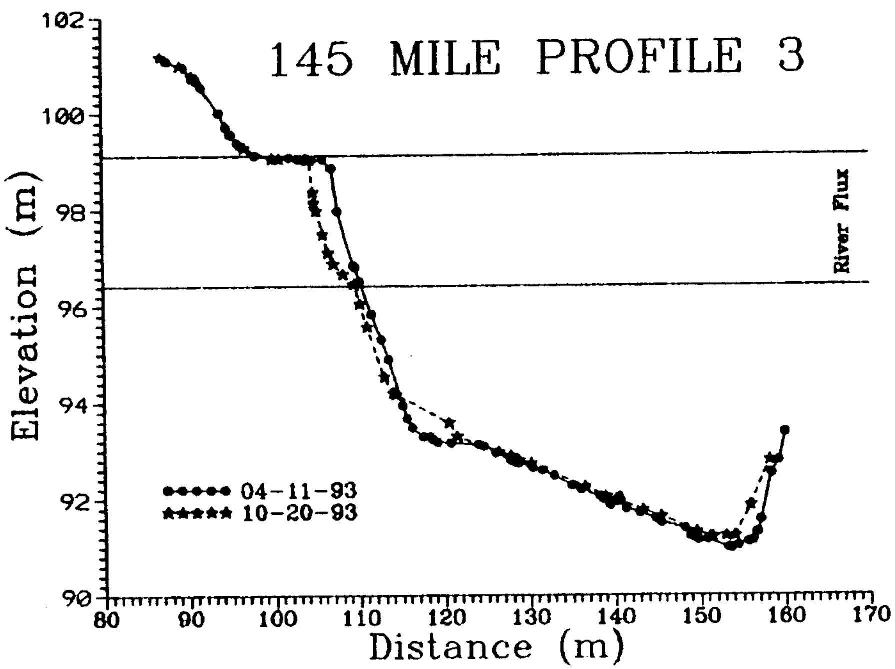


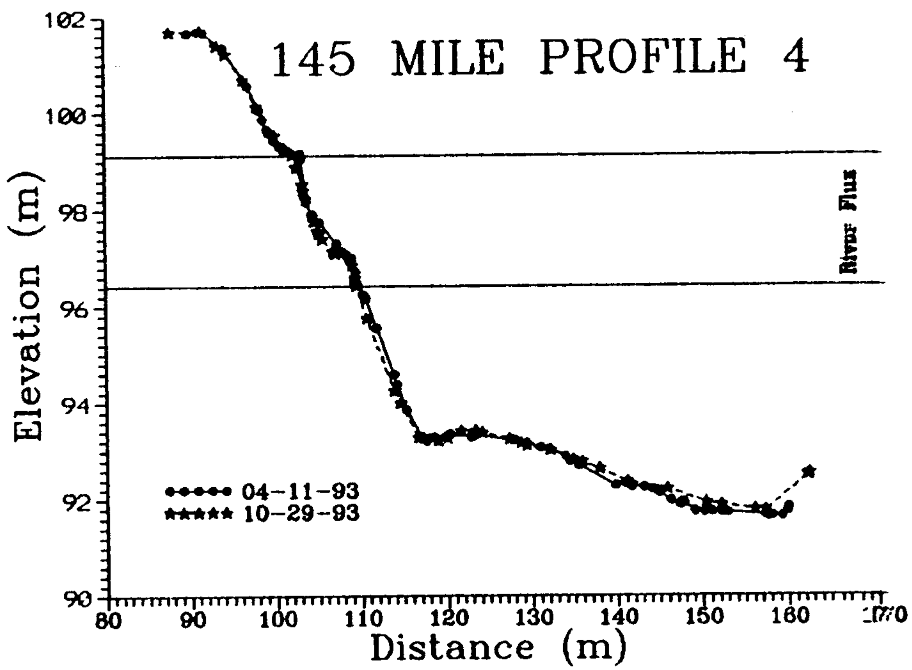
145L-B26

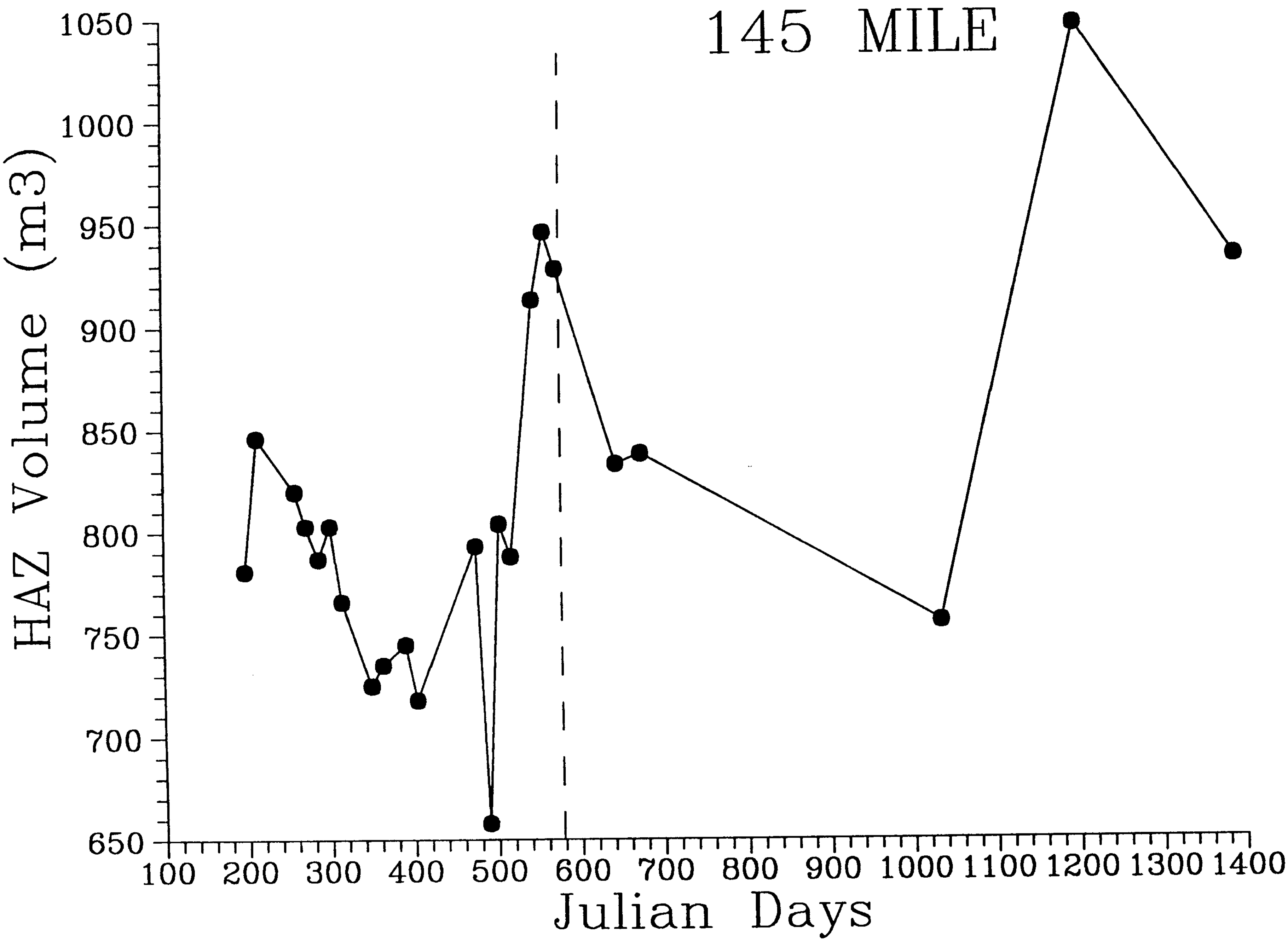
GCES BEACH SURVEY B26 145R 10-20-93 1: 300

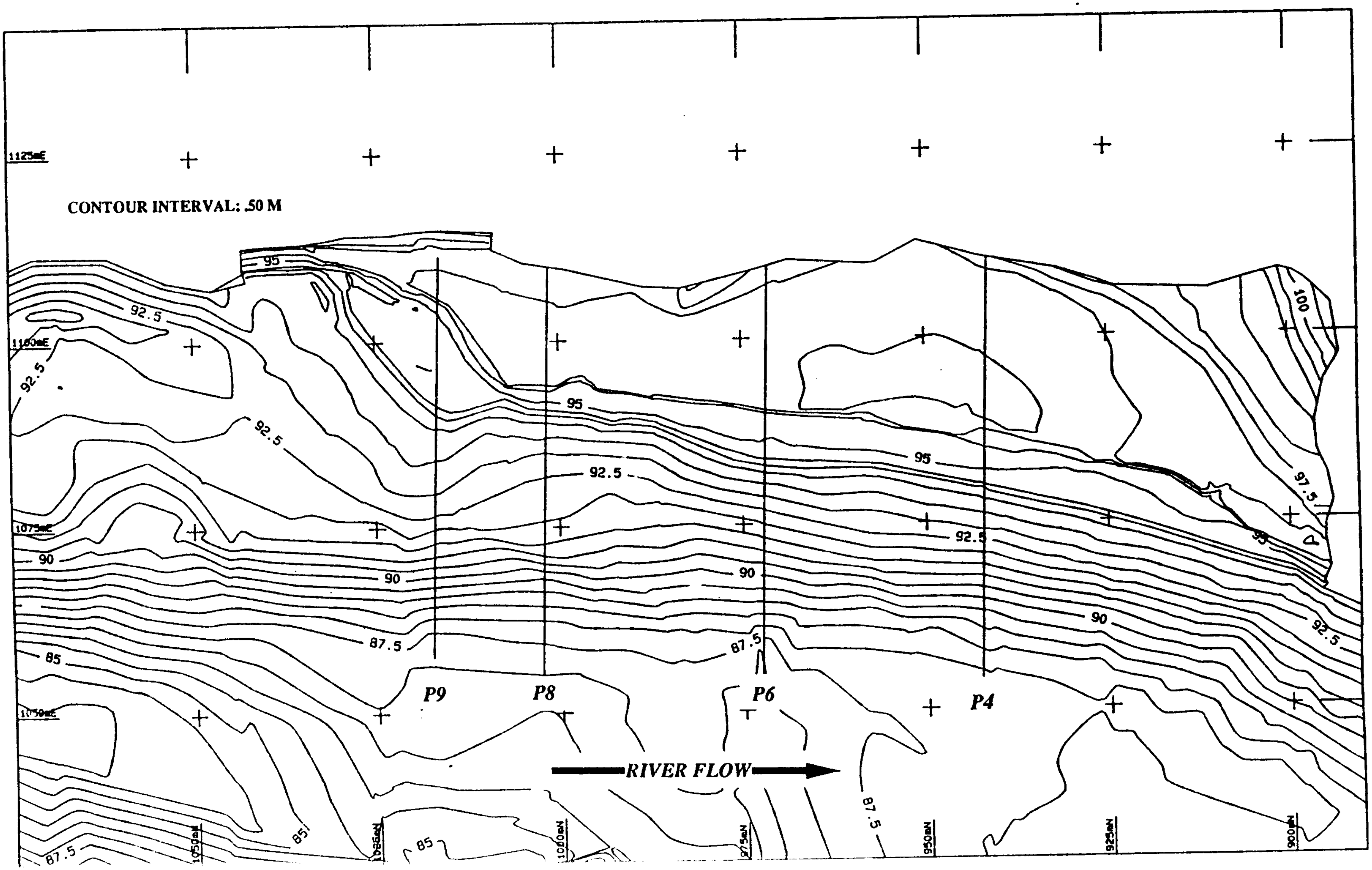

145 MILE PROFILE 1
Elevation (m)
Distance (m)
River Flux
04-11-93
10-20-93

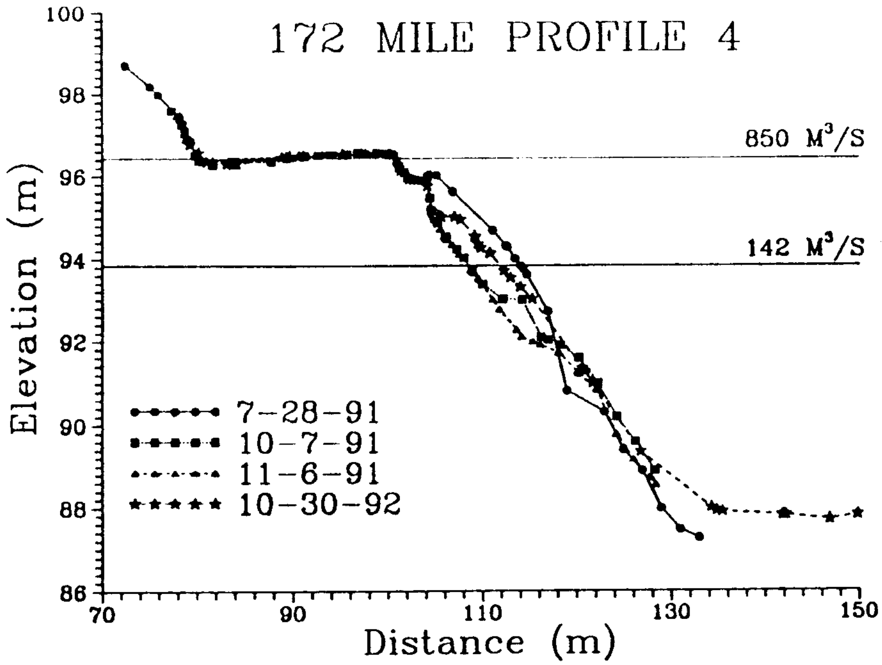

145 MILE PROFILE 2
Elevation (m)
Distance (m)
River Flux
04-11-93
10-20-93


145 MILE PROFILE 3
Elevation (m)
Distance (m)
River Flux
04-11-93
10-20-93

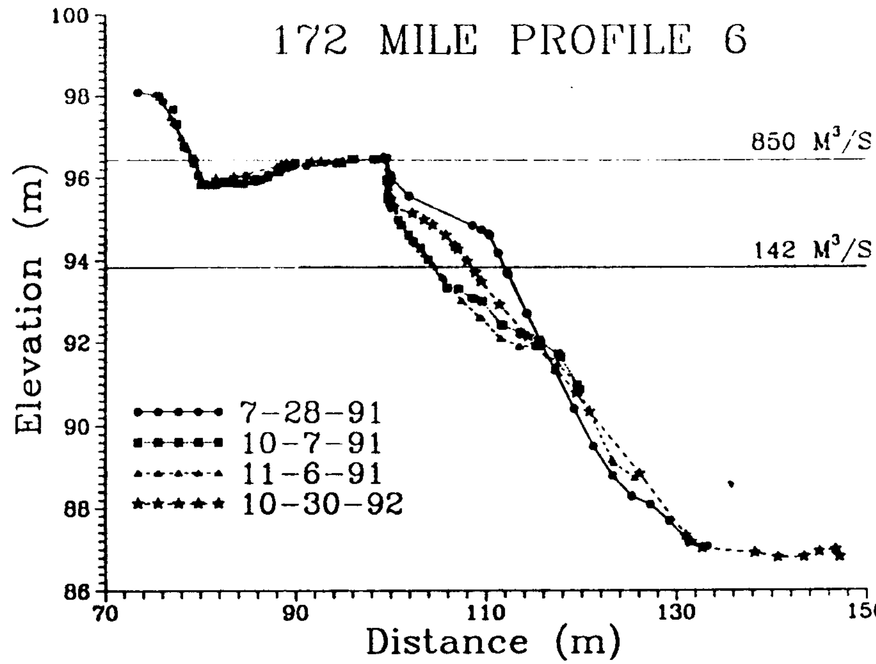

145 MILE PROFILE 4
Elevation (m)
Distance (m)
River Flux
04-11-93
10-29-93


145 MILE
HAZ Volume (m3)
1050
1000
950
900
850
800
750
700
650
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400
Julian Days

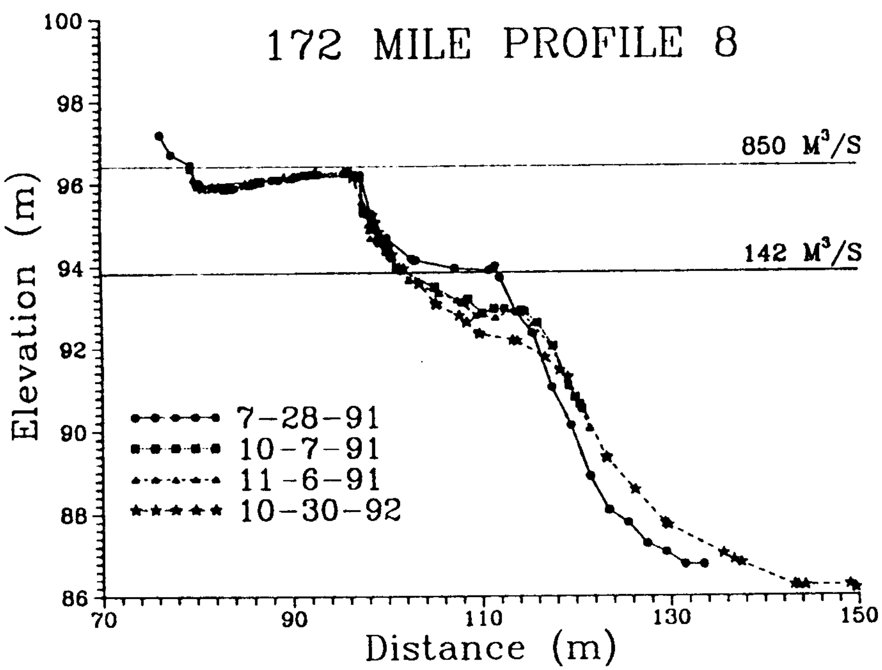

CONTOUR INTERVAL: .50 M
1125mE
1100mE
1075mE
1050mE
1050mN
1025mN
1000mN
975mN
950mN
925mN
900mN
100
97.5
95
92.5
90
87.5
85
P9
P8
P6
P4
RIVER FLOW



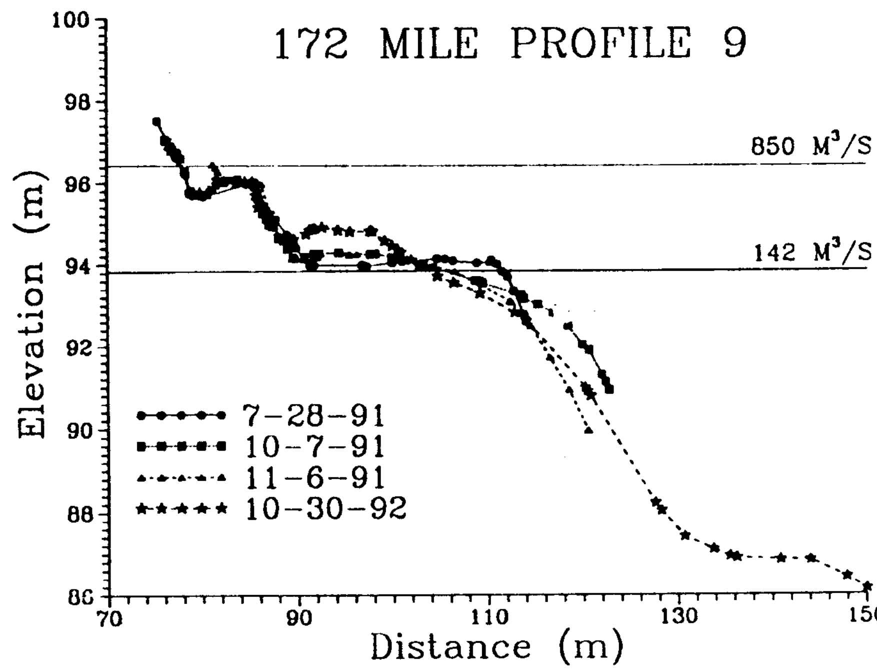
172 MILE PROFILE 4
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
7-28-91
10-7-91
11-6-91
10-30-92



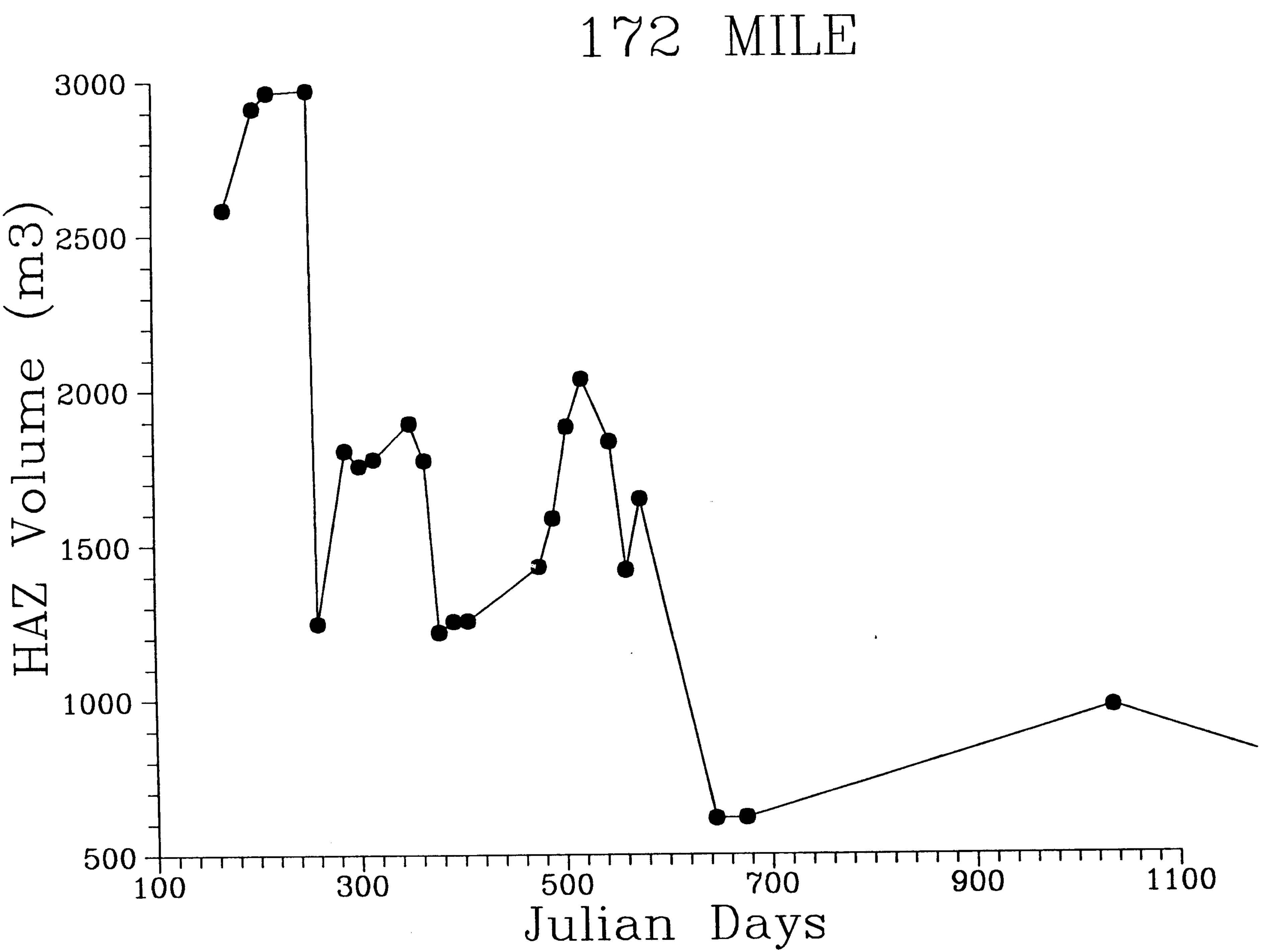
172 MILE PROFILE 6
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
7-28-91
10-7-91
11-6-91
10-30-92



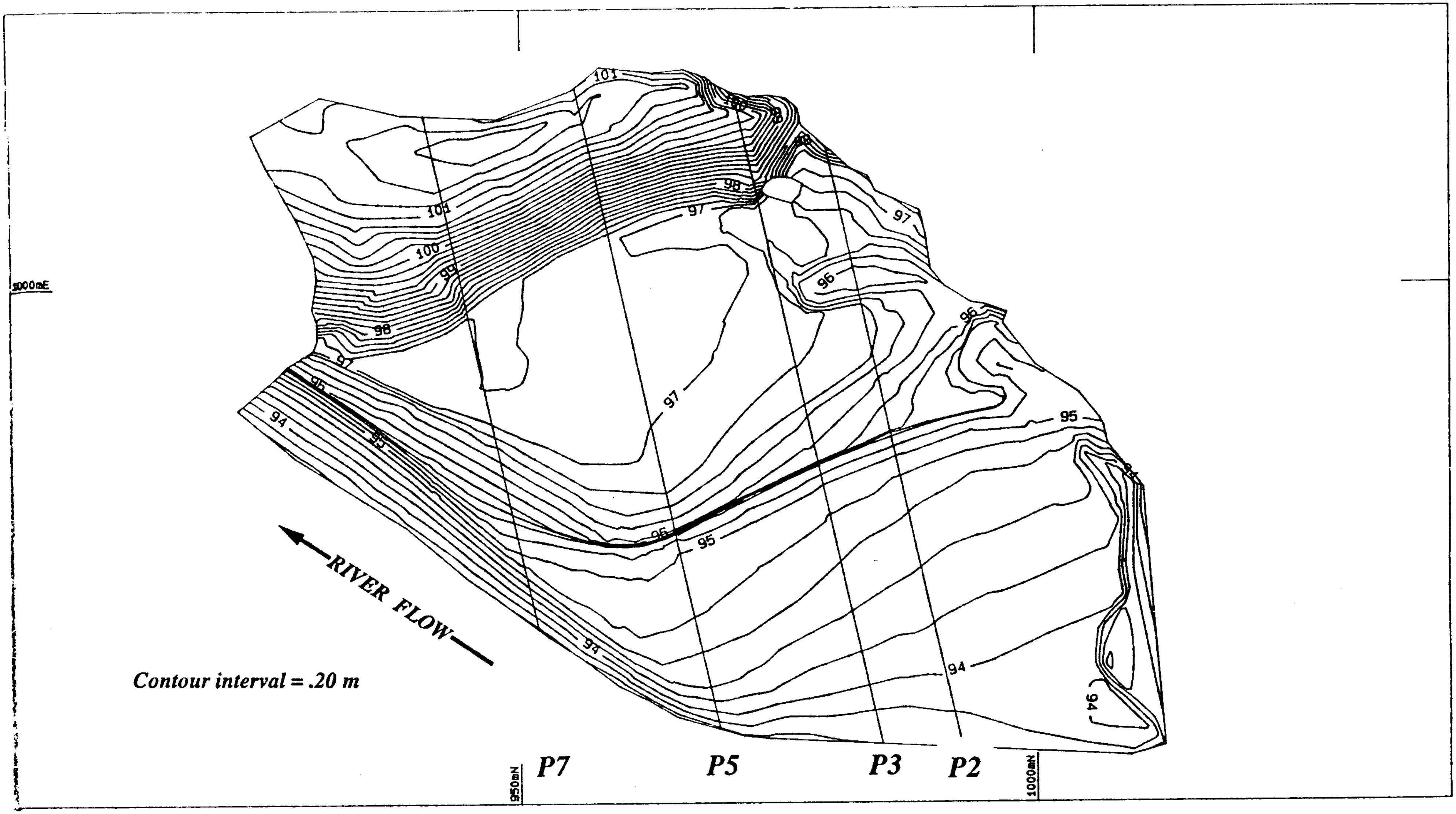
172 MILE PROFILE 8
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
7-28-91
10-7-91
11-6-91
10-30-92



172 MILE PROFILE 9
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
7-28-91
10-7-91
11-6-91
10-30-92

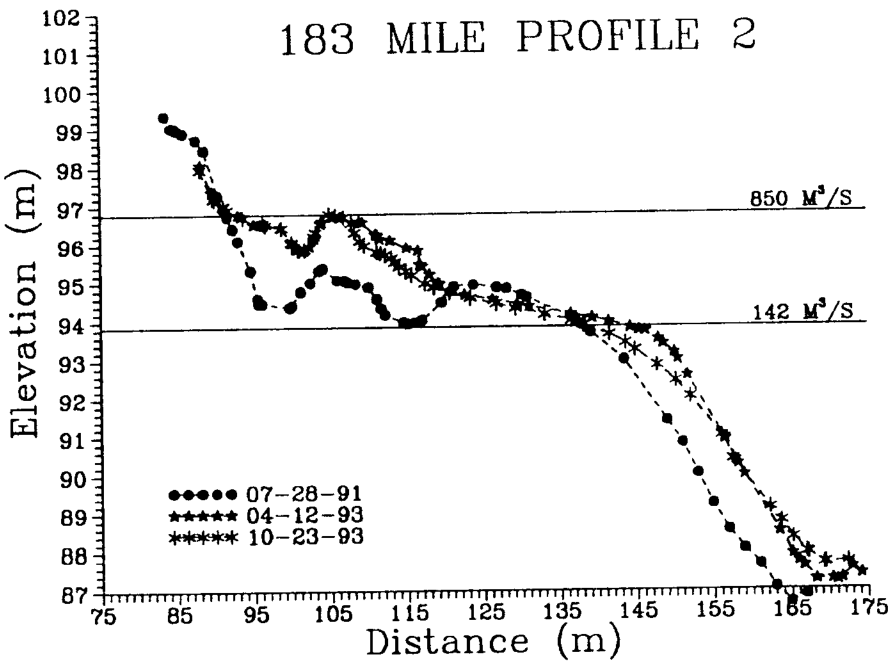


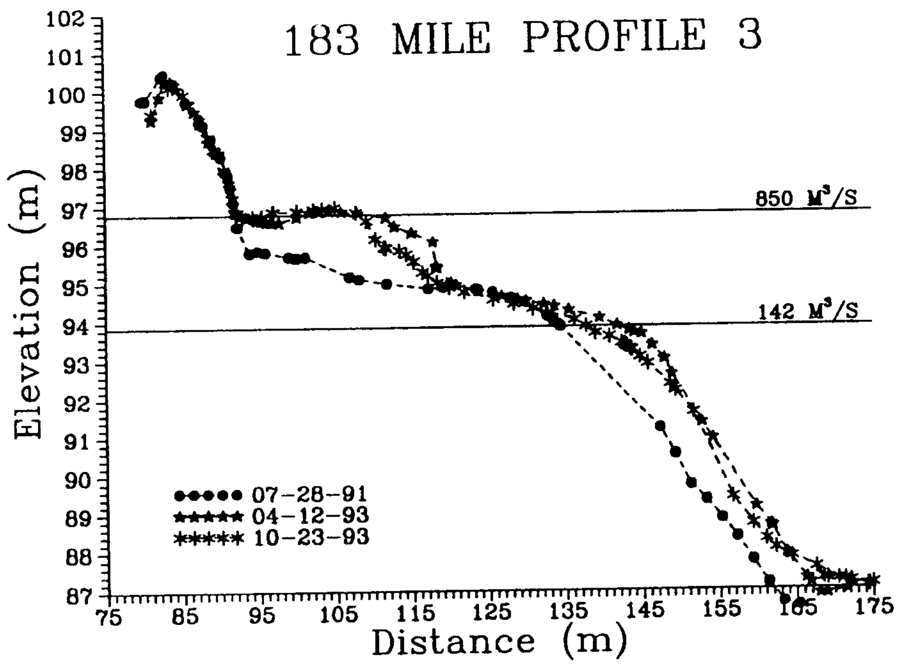
172 MILE
HAZ Volume (m3)
3000
2500
2000
1500
1000
500
100
300
500
700
900
1100
Julian Days

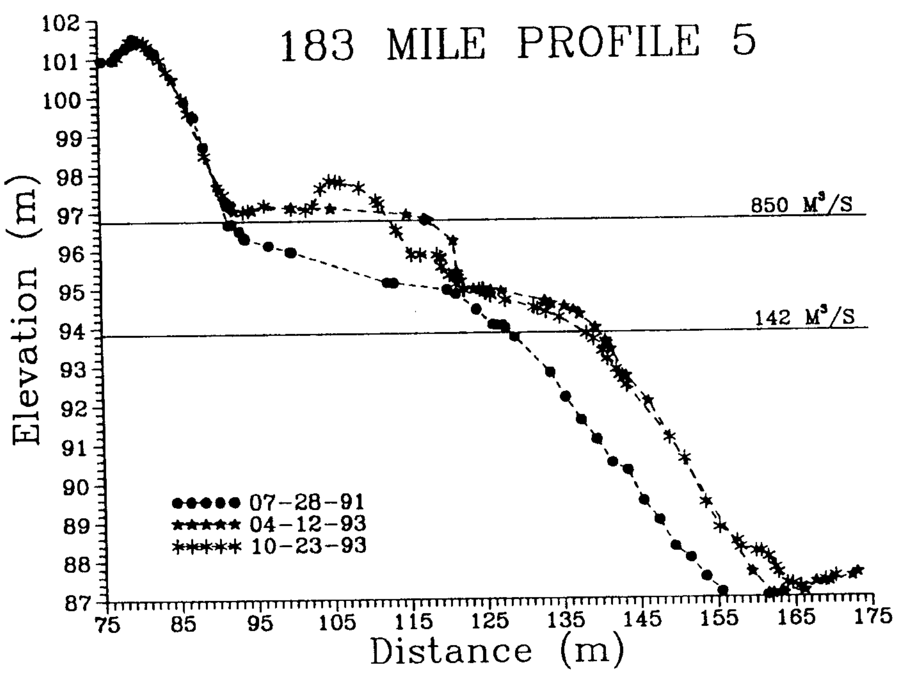


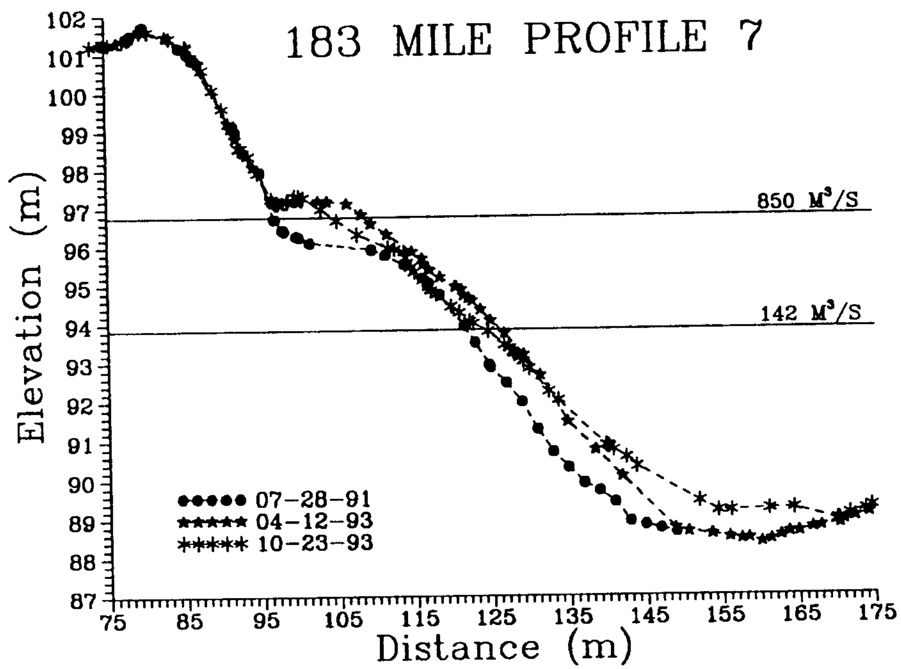
Plot 4

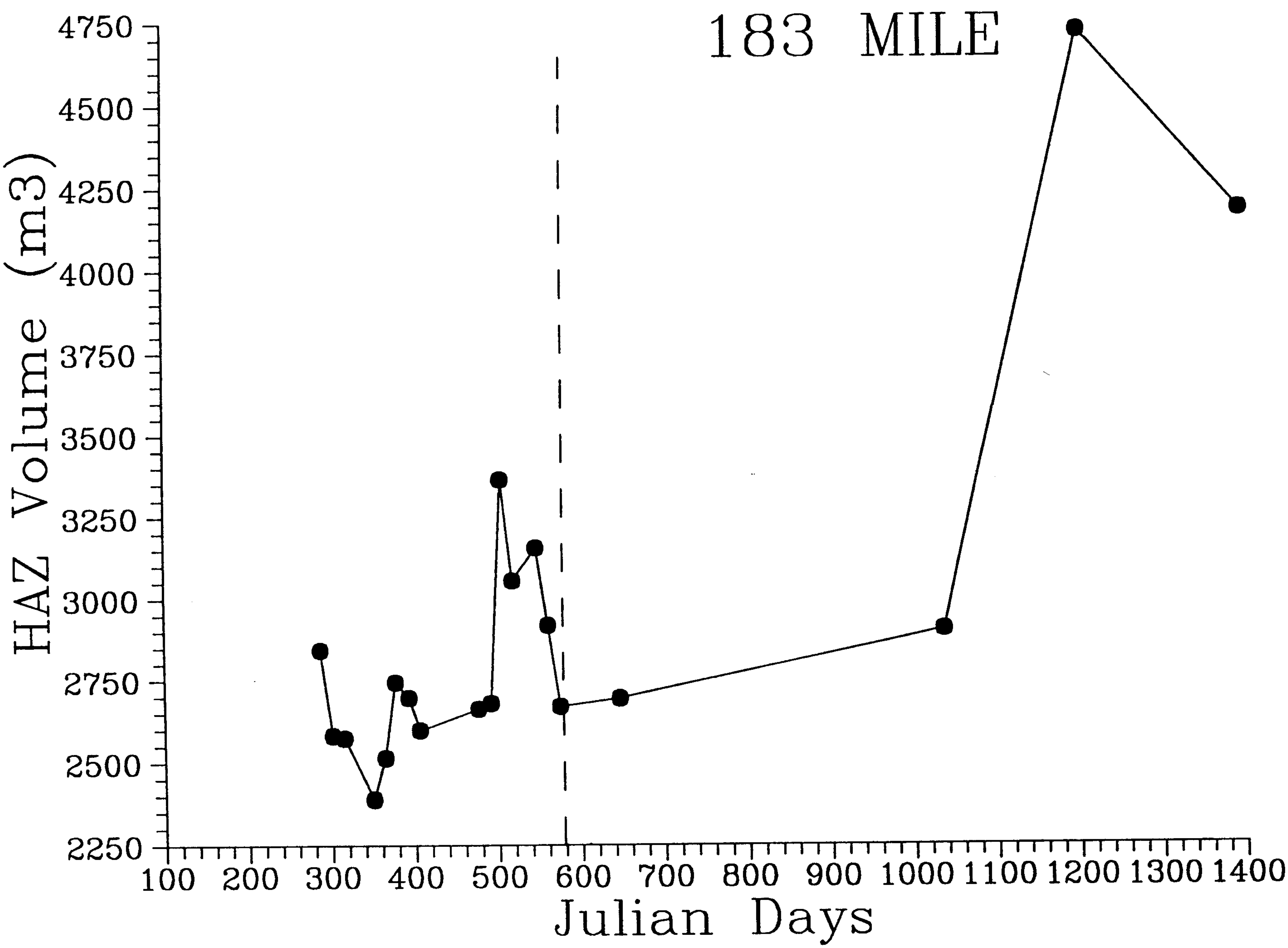
GCES BEACH SURVEY 28Z 183 MILE 4-12-93 1: 350


183 MILE PROFILE 2
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
07-28-91
04-12-93
10-23-93

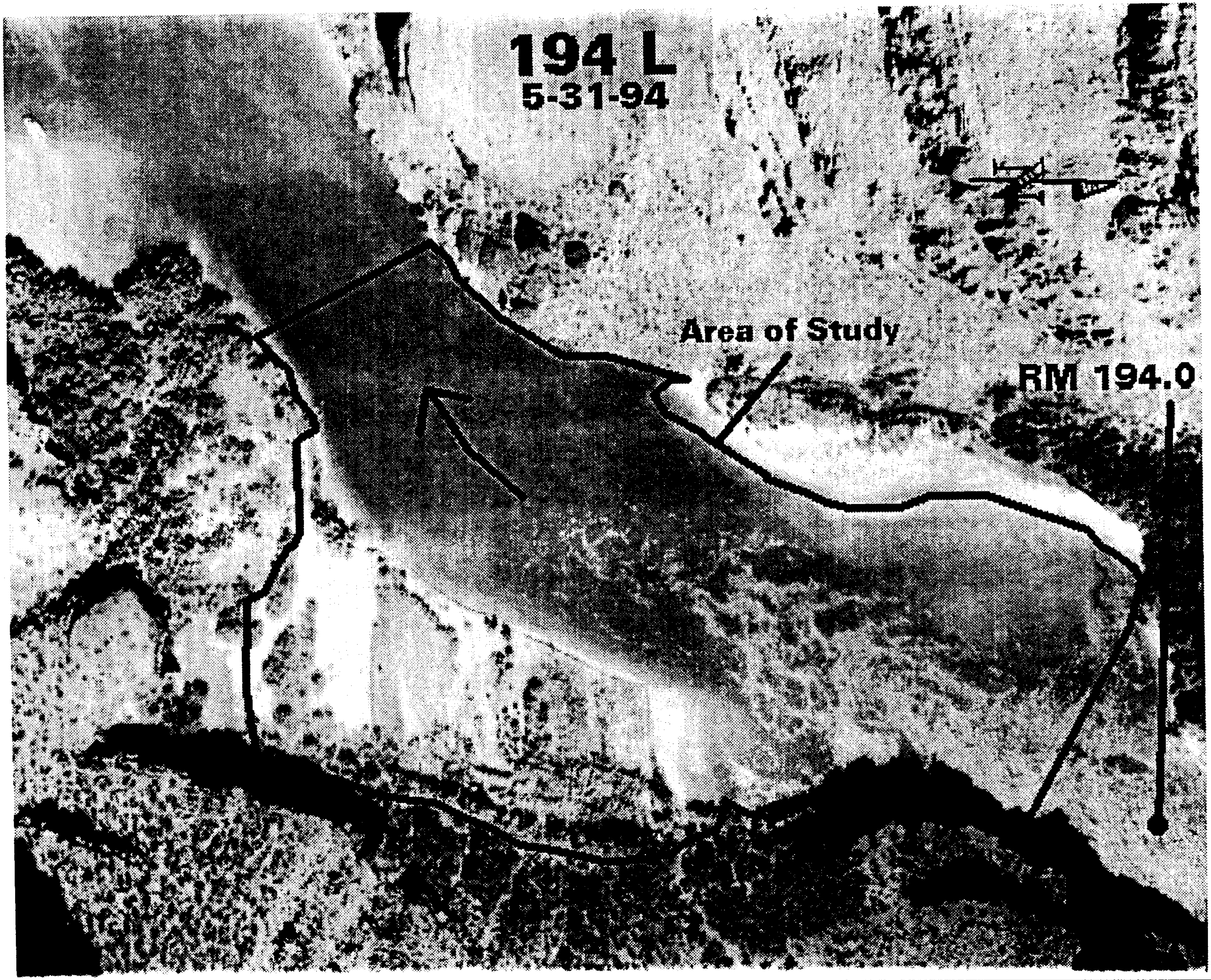

183 MILE PROFILE 3
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
07-28-91
04-12-93
10-23-93

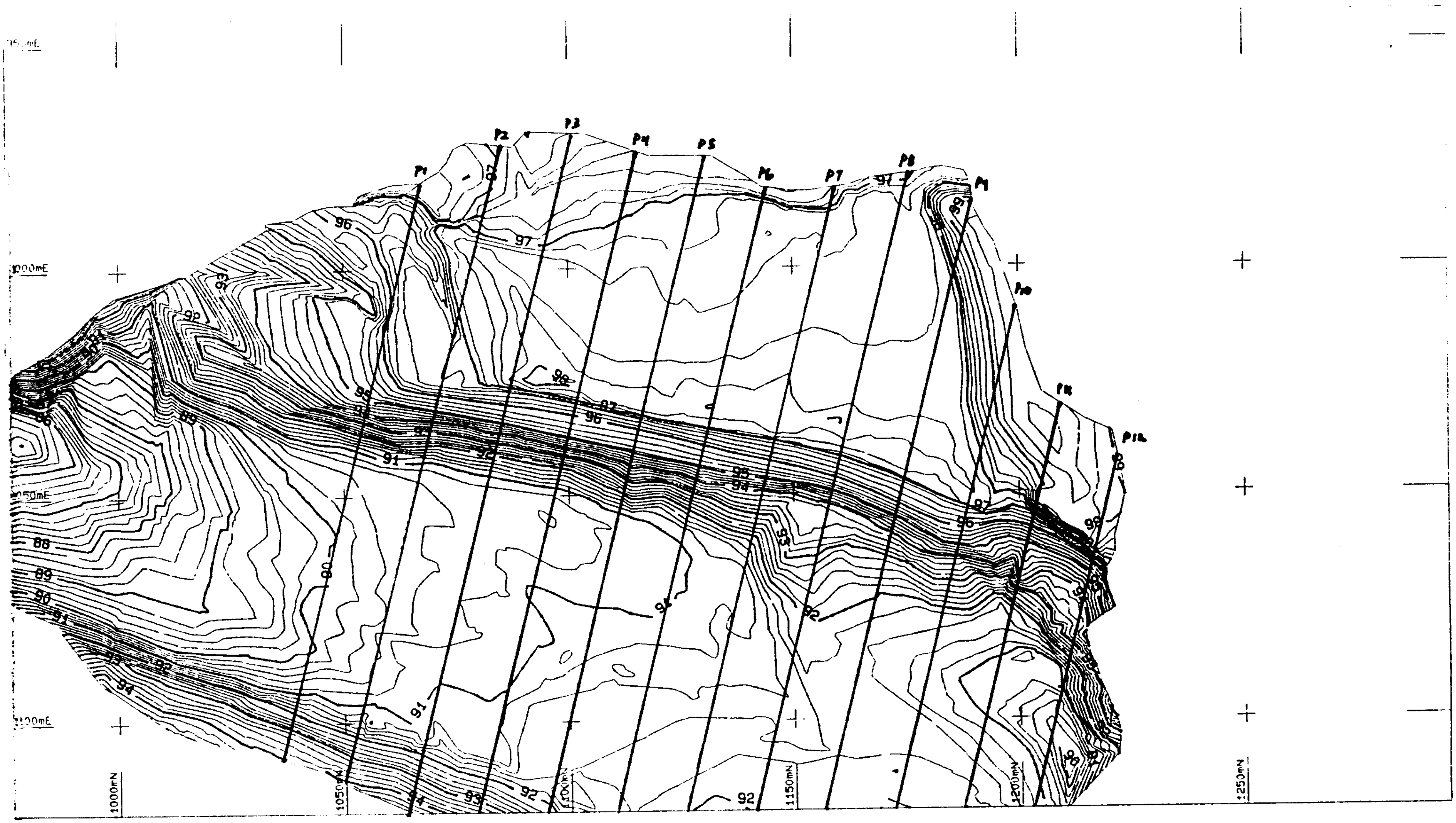

183 MILE PROFILE 5
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
07-28-91
04-12-93
10-23-93


183 MILE PROFILE 7
Elevation (m)
Distance (m)
850 M³/S
142 M³/S
07-28-91
04-12-93
10-23-93



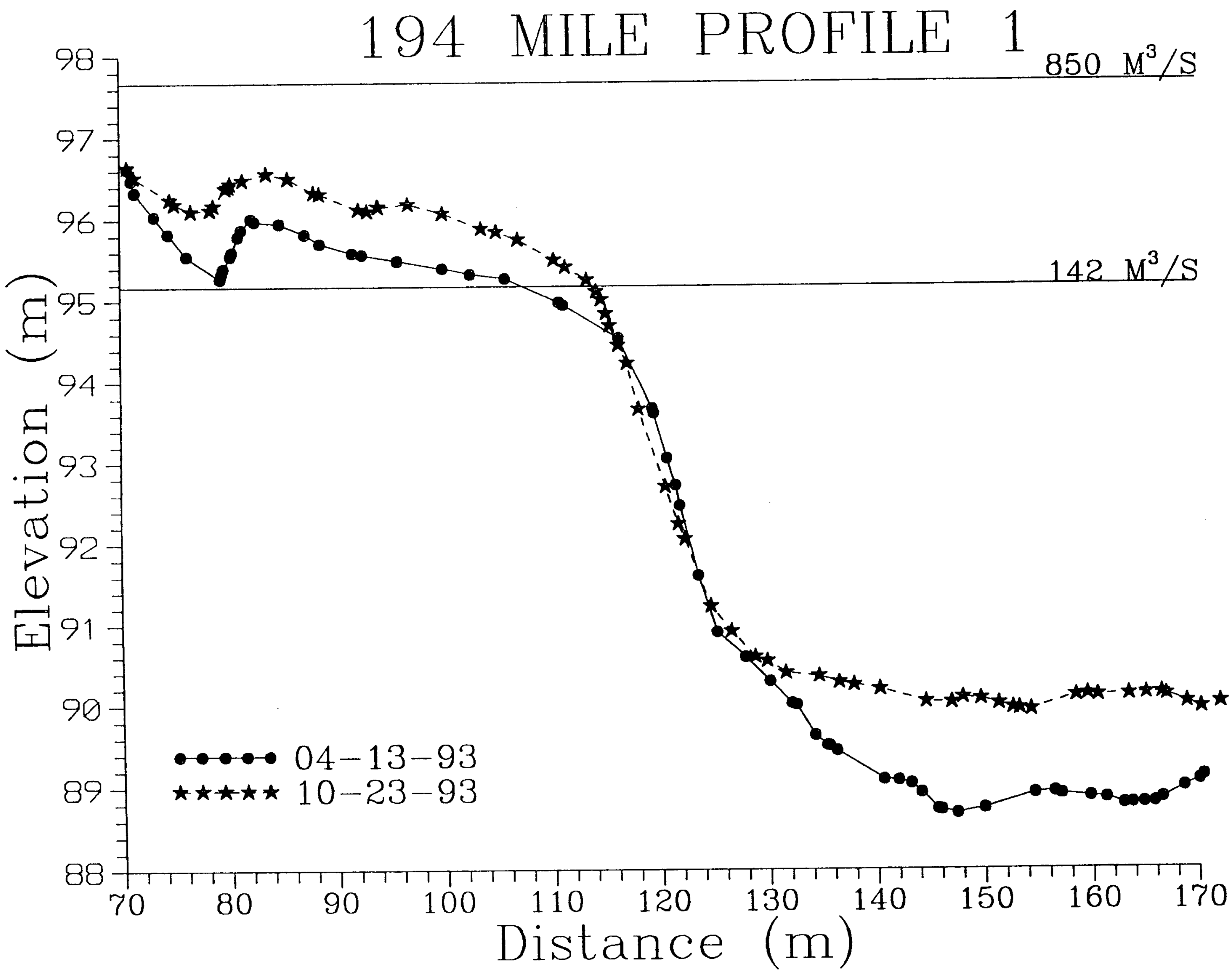
183 MILE
HAZ Volume (m3)
Julian Days
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
2250
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400


194 L
5-31-94
Area of Study
RM 194.0
N

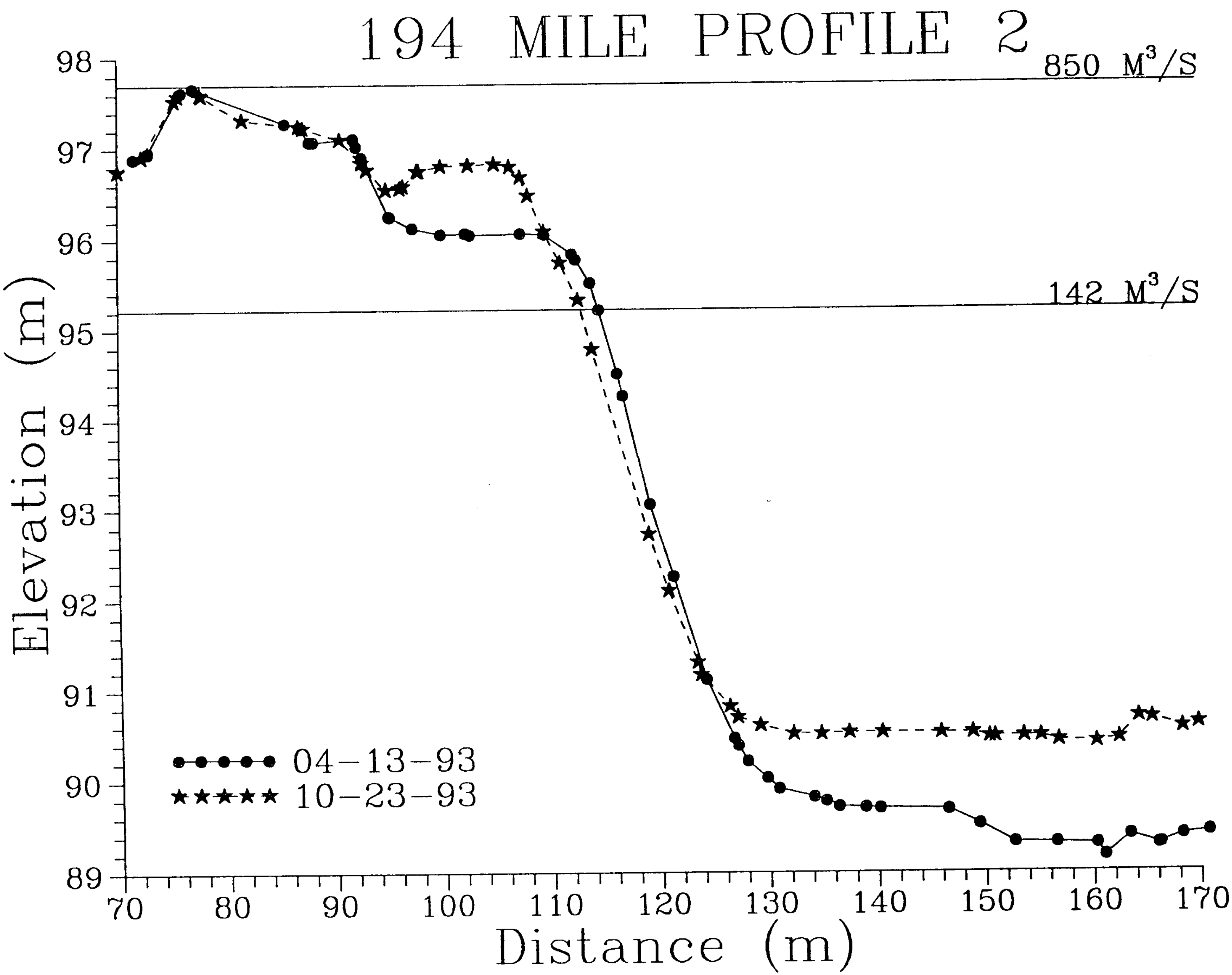


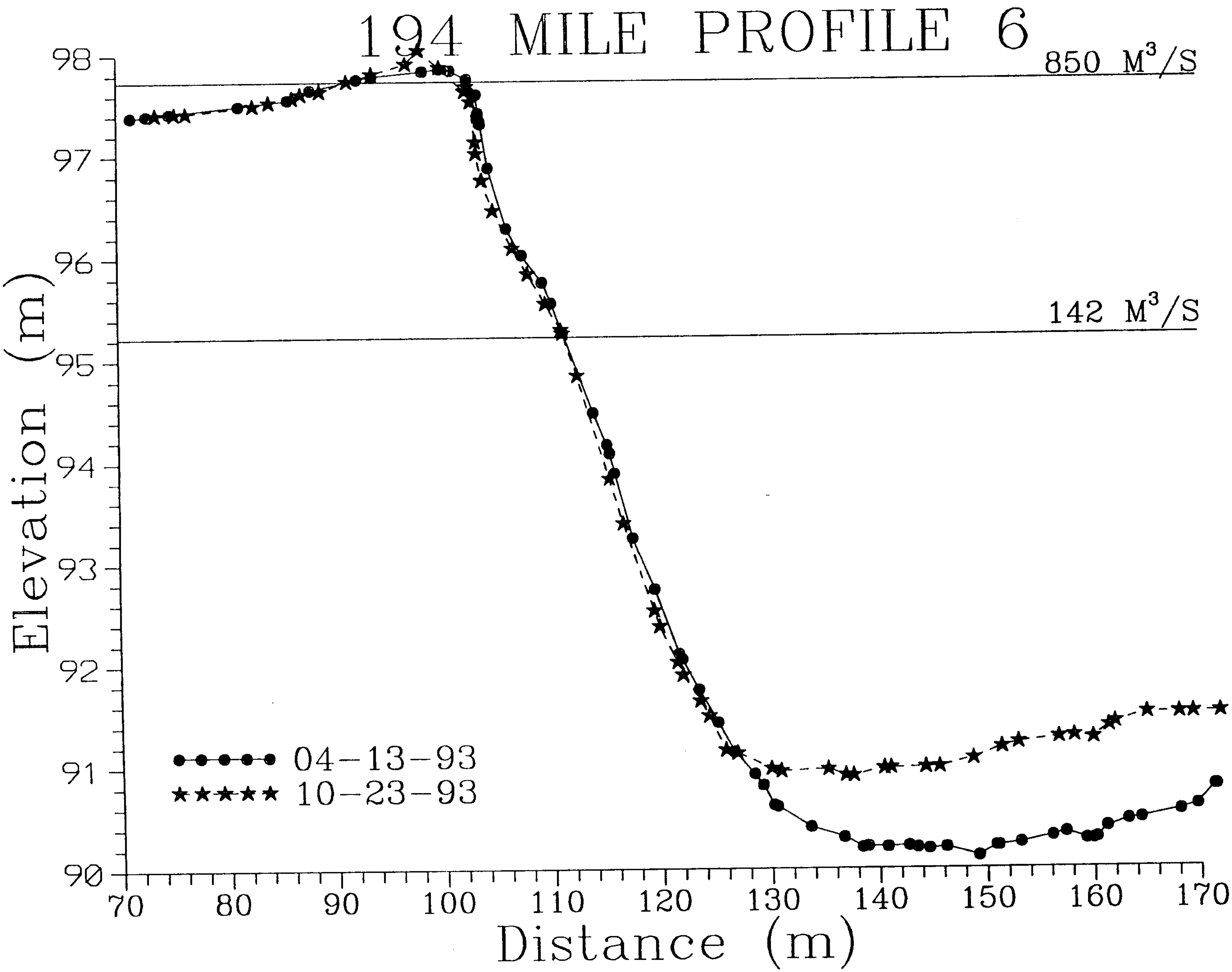
194L-B29

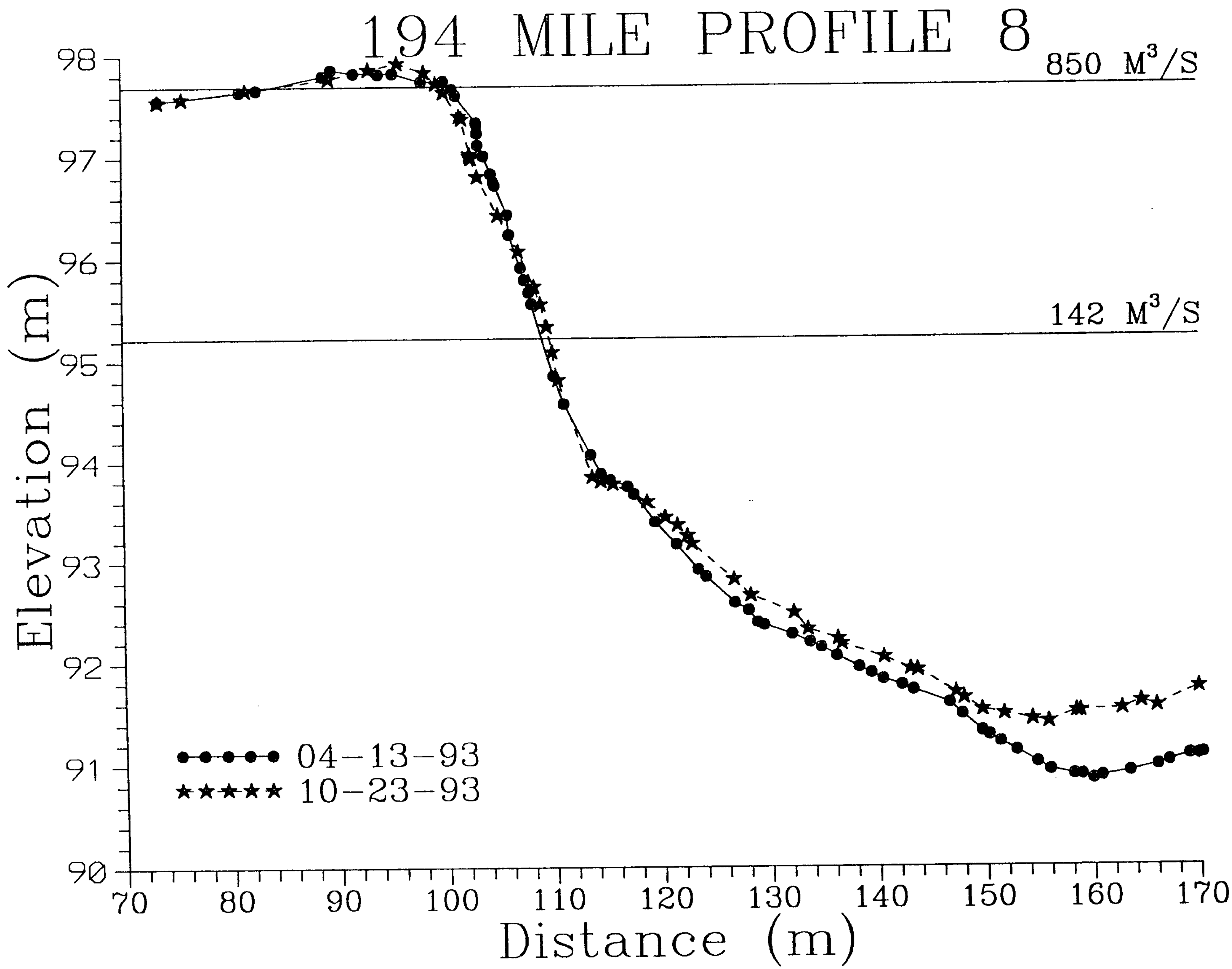
GCES BEACH SURVEY B29 194 MILE 10-23-93 1: 800

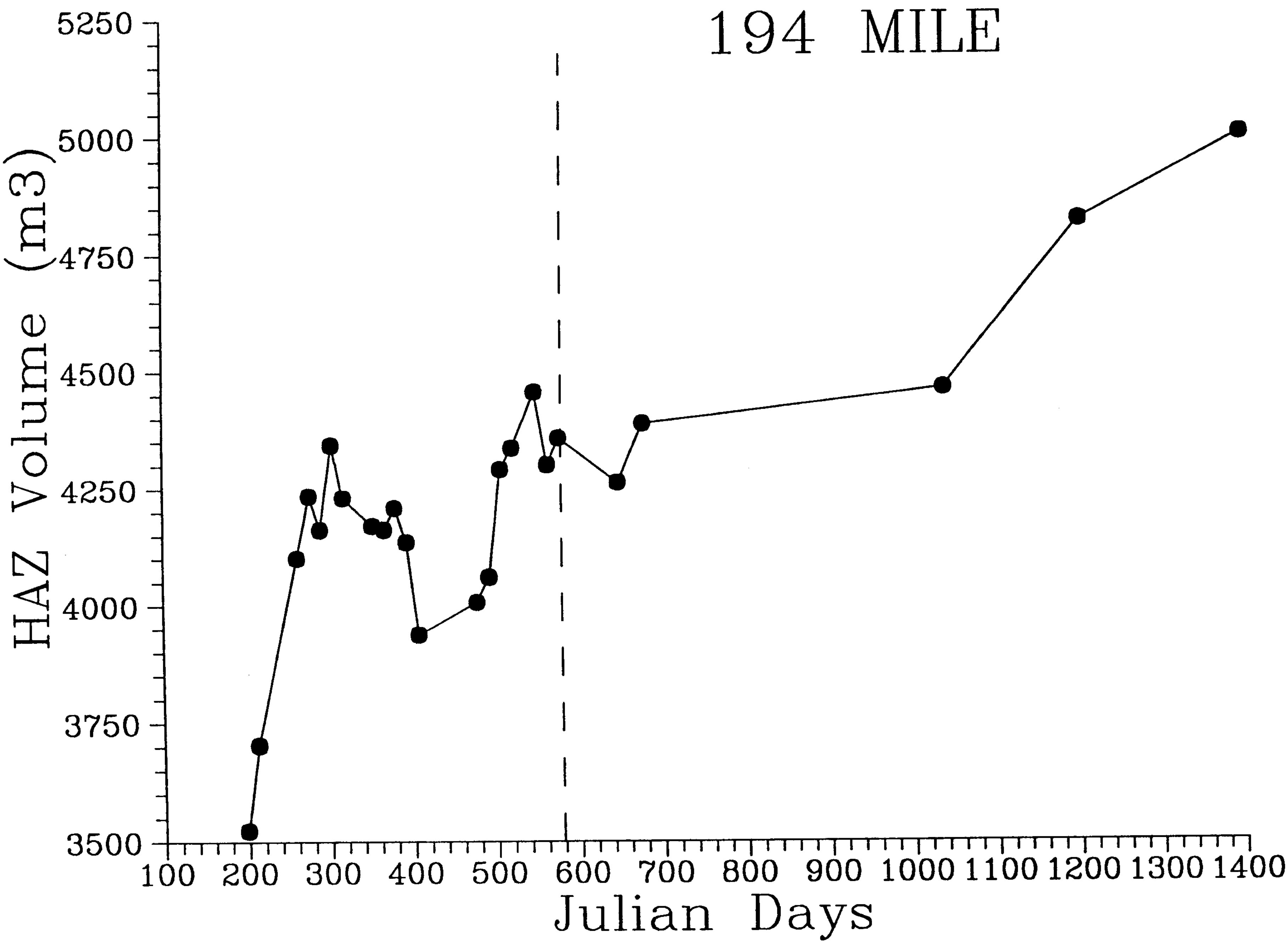


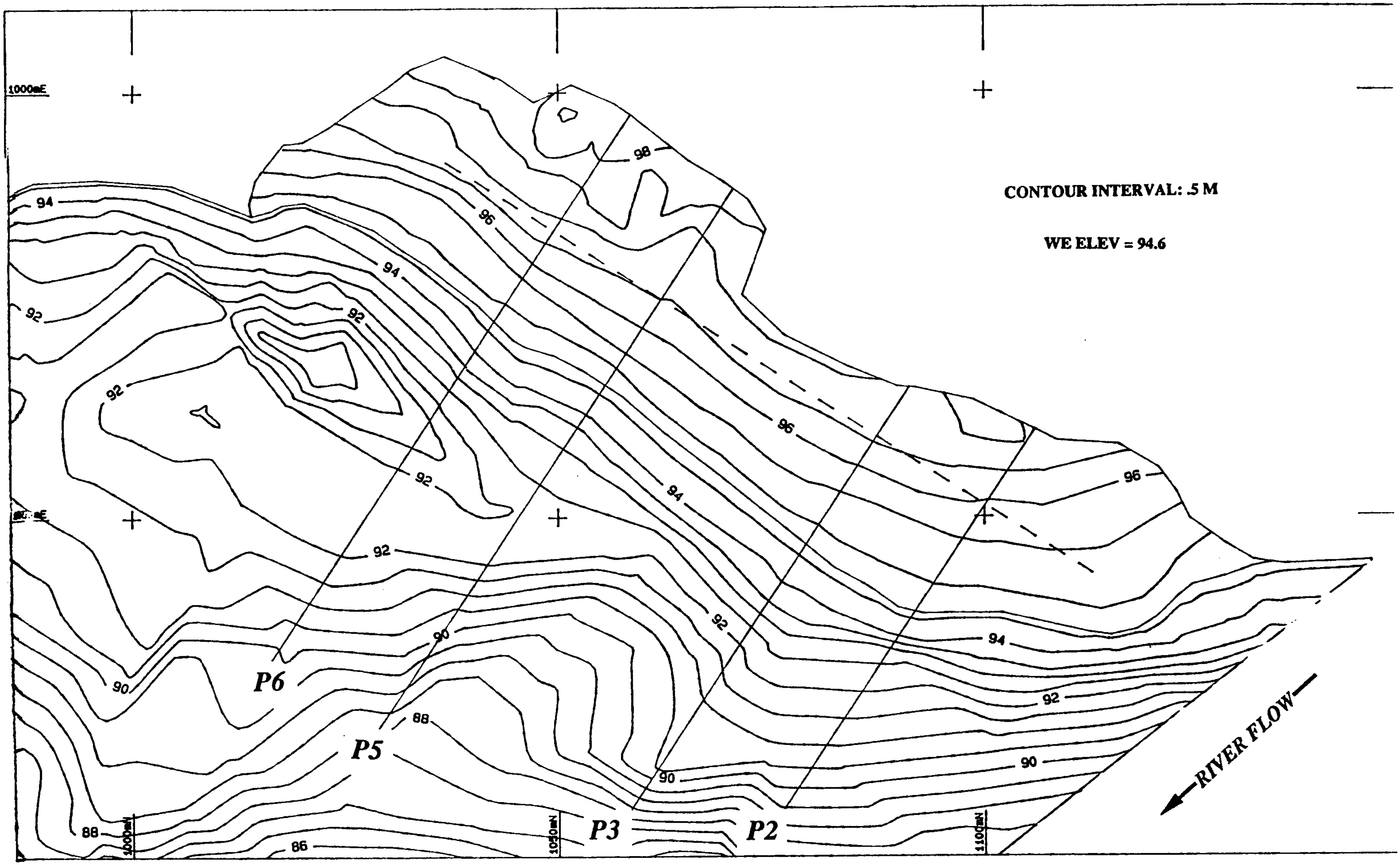
194 MILE PROFILE 1
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
04-13-93
10-23-93
98
97
96
95
94
93
92
91
90
89
88
70
80
90
100
110
120
130
140
150
160
170

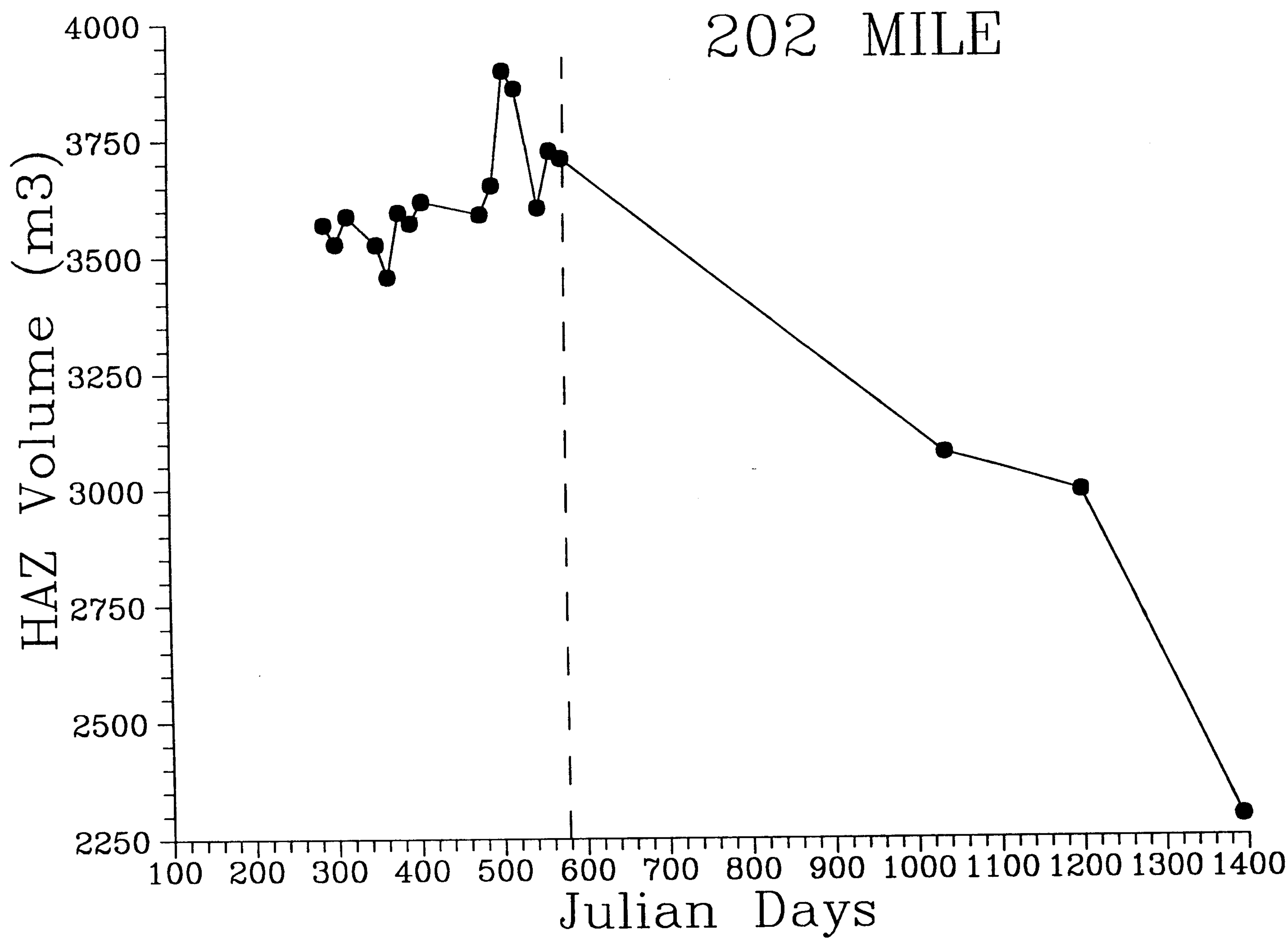

194 MILE PROFILE 2
850 M³/S
142 M³/S
04-13-93
10-23-93
Elevation (m)
Distance (m)
98
97
96
95
94
93
92
91
90
89
70
80
90
100
110
120
130
140
150
160
170


194 MILE PROFILE 6
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
04-13-93
10-23-93
98
97
96
95
94
93
92
91
90
70
80
90
100
110
120
130
140
150
160
170


194 MILE PROFILE 8
850 M3/S
142 M3/S
Elevation (m)
Distance (m)
04-13-93
10-23-93
98
97
96
95
94
93
92
91
90
70
80
90
100
110
120
130
140
150
160
170

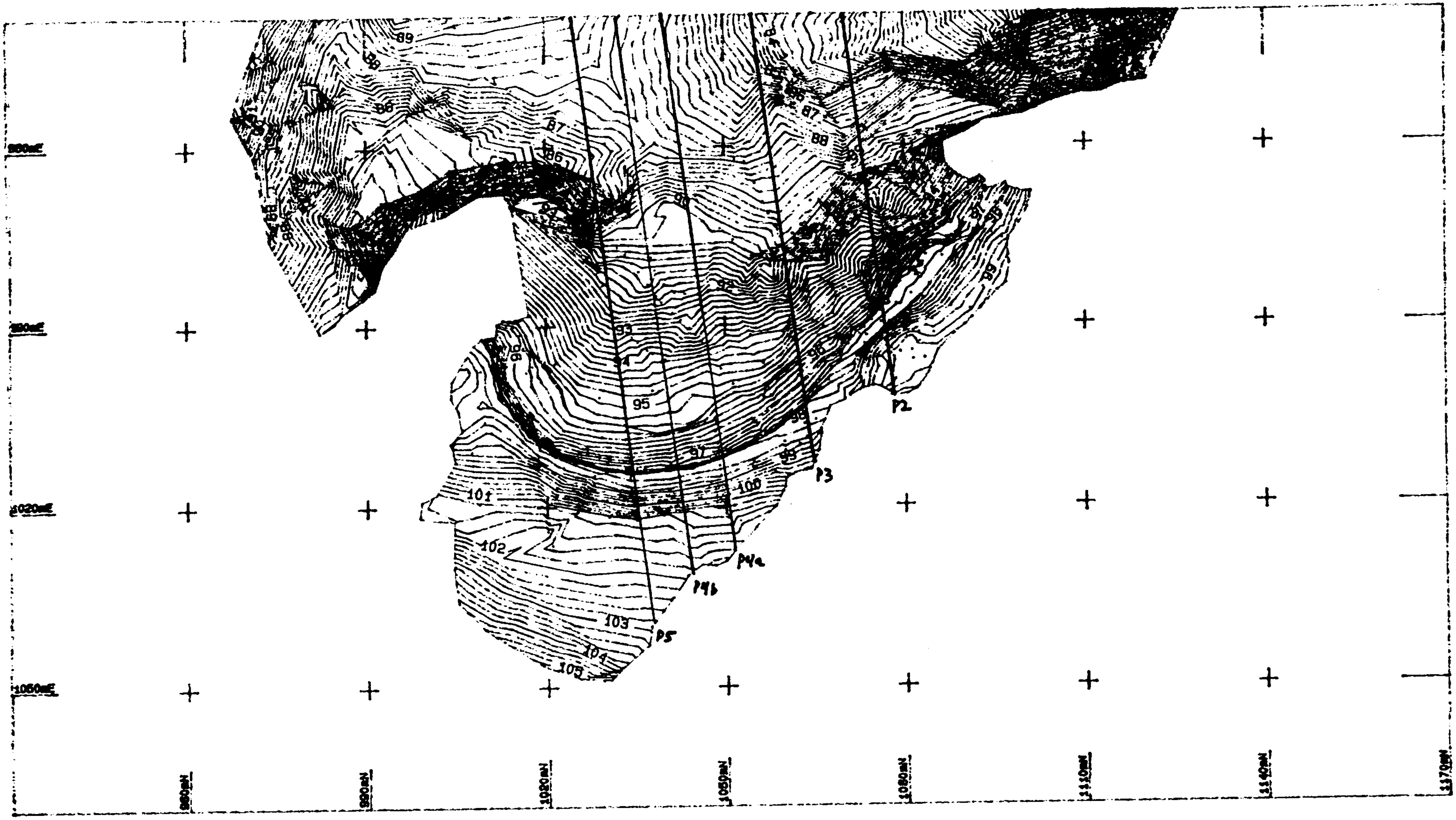

194 MILE
HAZ Volume (m3)
5250
5000
4750
4500
4250
4000
3750
3500
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days


CONTOUR INTERVAL: .5 M
WE ELEV = 94.6
RIVER FLOW
P2
P3
P5
P6
1000mE
1000mN
1050mN
1100mN
98
96
94
92
90
88
86



202 MILE
HAZ Volume (m3)
4000
3750
3500
3250
3000
2750
2500
2250
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

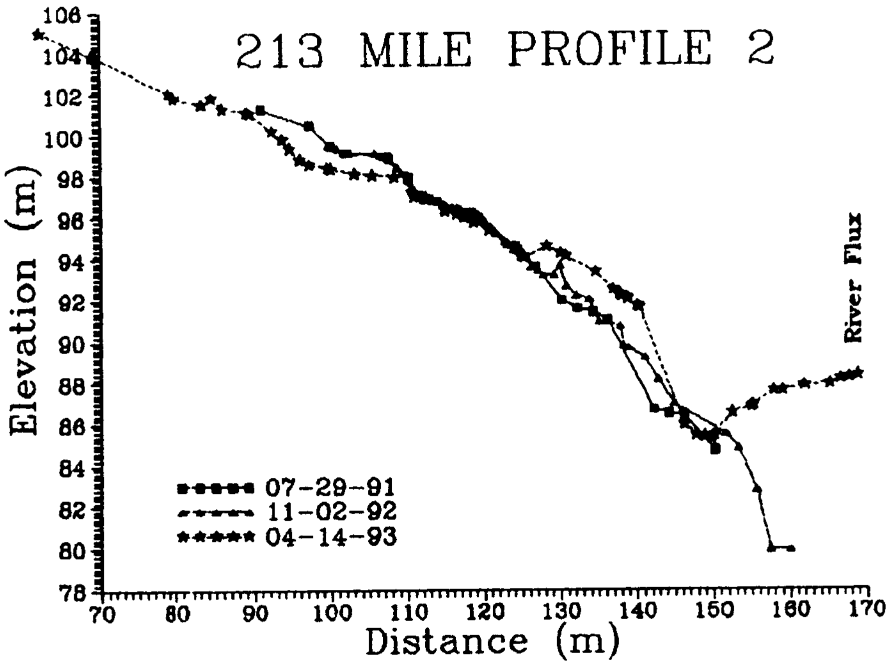

213 L
5-31-94
RM
Area of Study
N

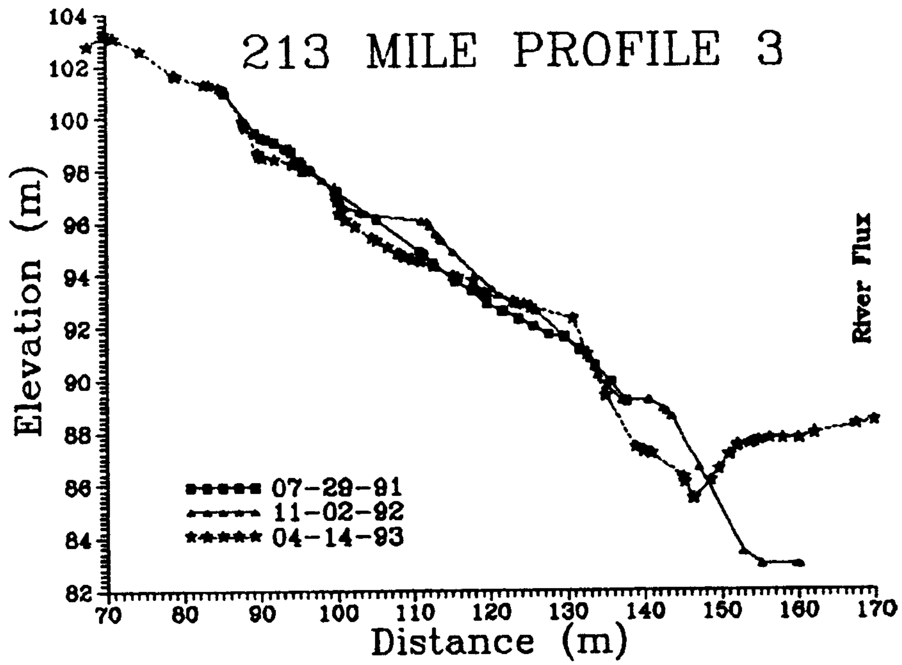


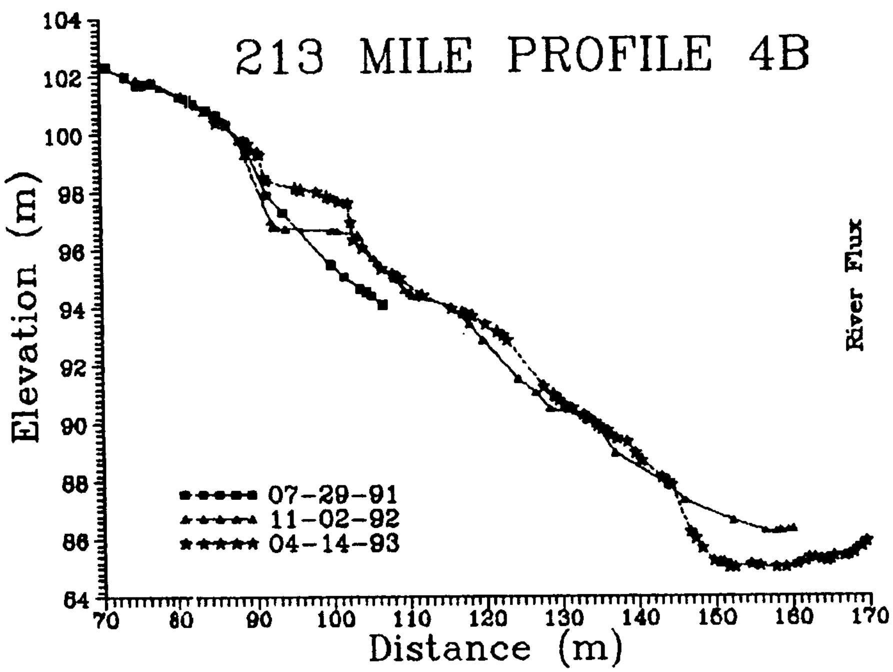
213L-B31

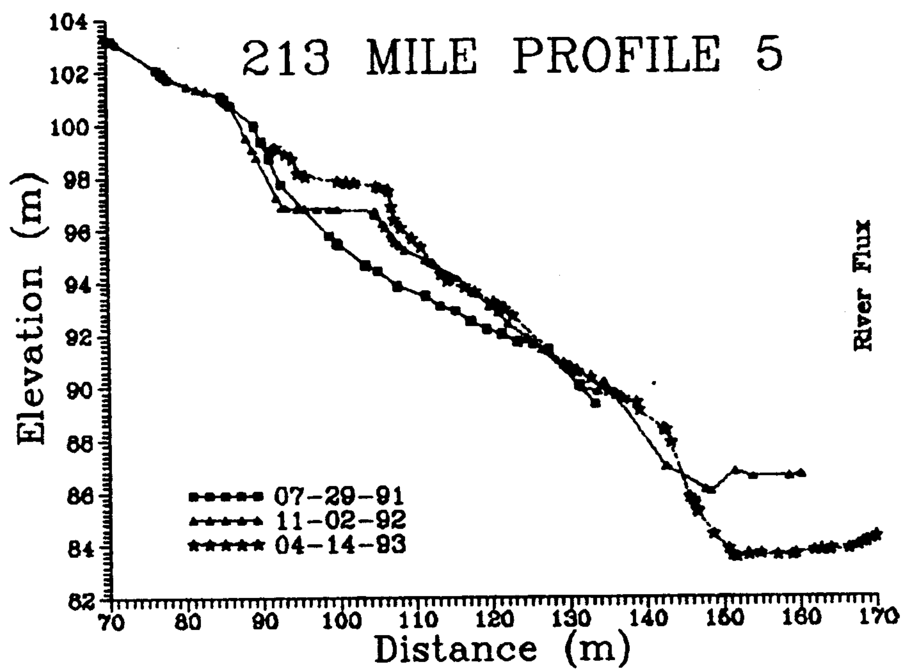
GCES BEACH SURVEY   B31   213 MILE L 10-25-93   1: 600

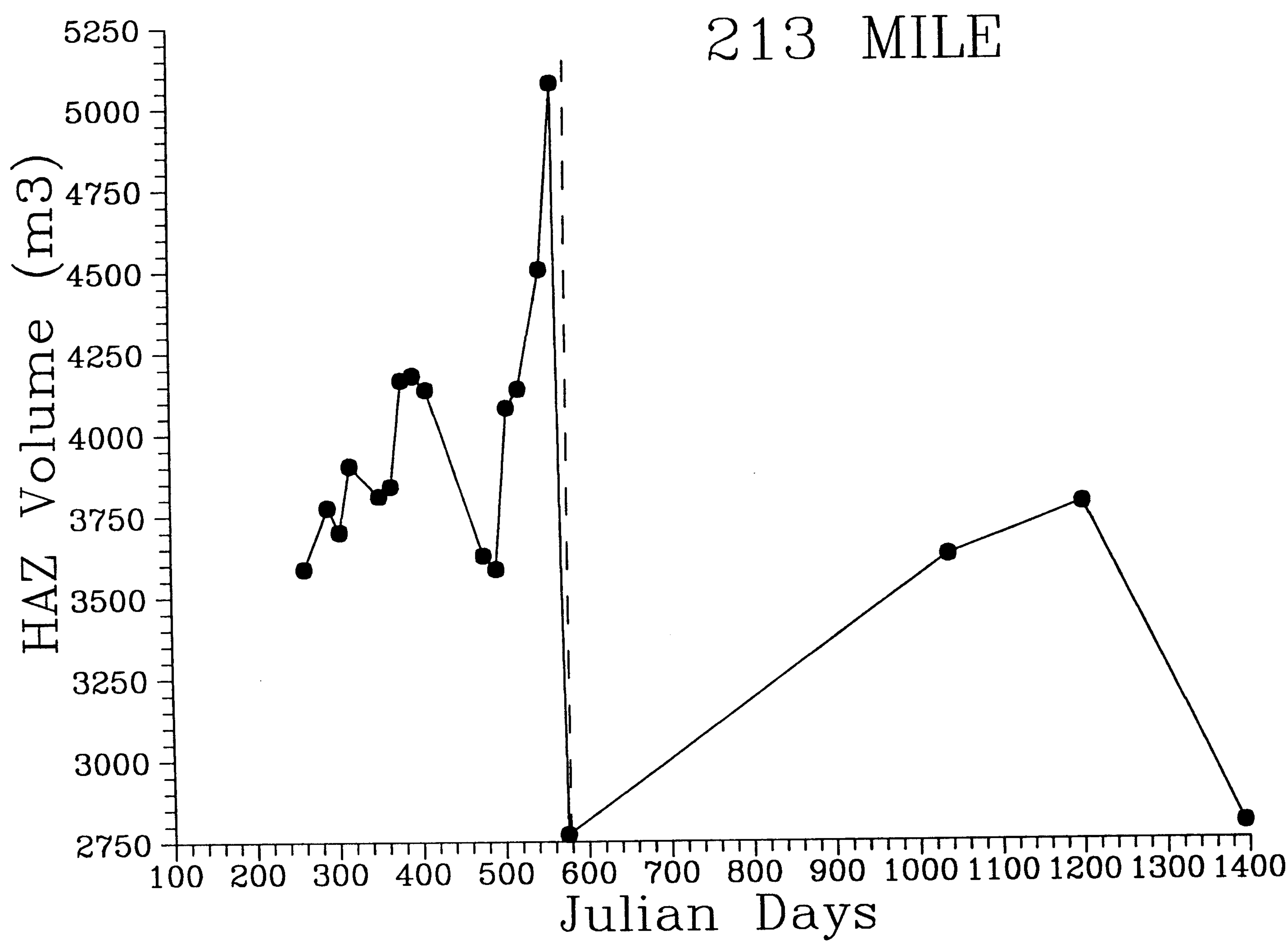
JEH 1-20-94


213 MILE PROFILE 2
Elevation (m)
Distance (m)
River Flux
07-29-91
11-02-92
04-14-93

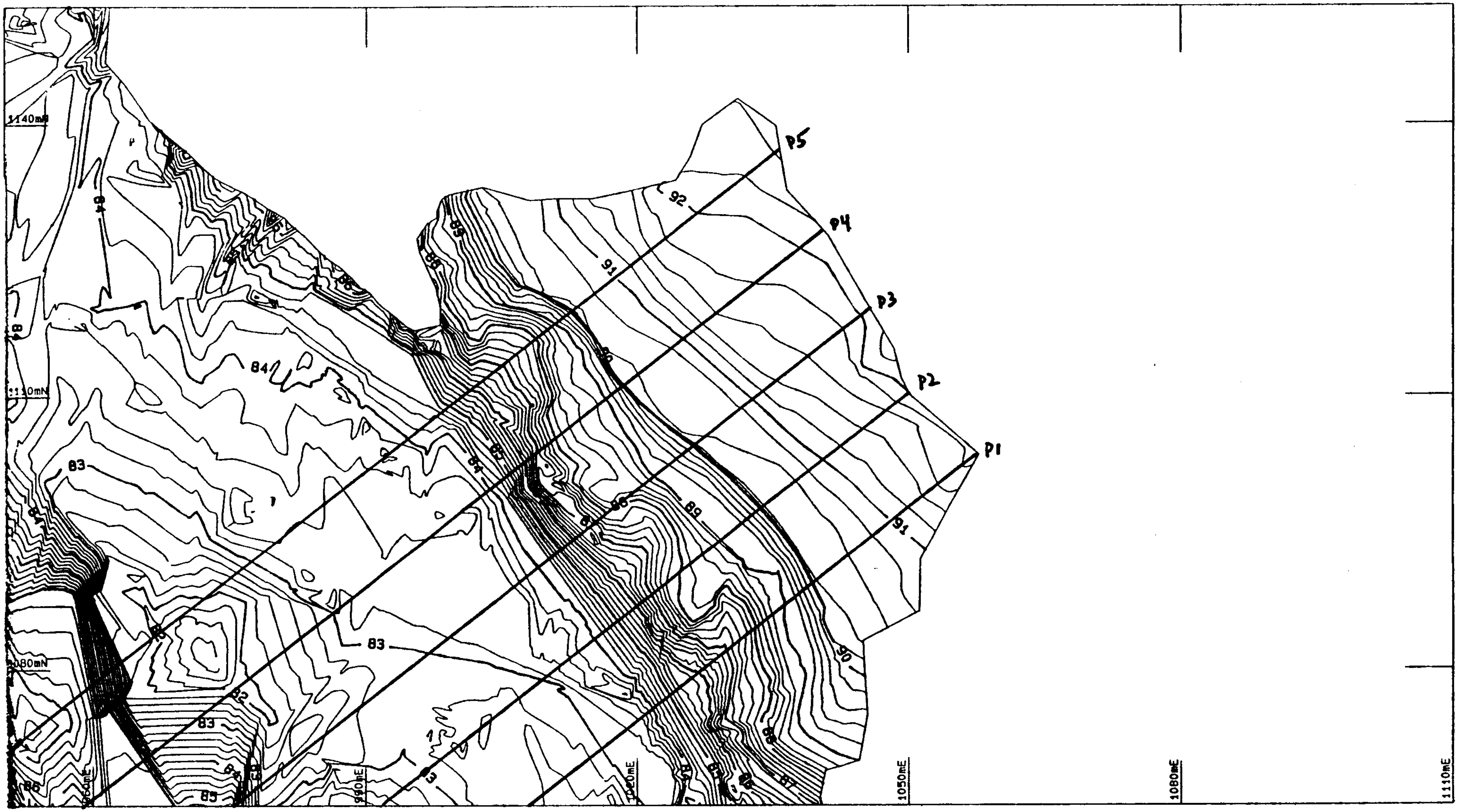

213 MILE PROFILE 3
Elevation (m)
Distance (m)
River Flux
07-29-91
11-02-92
04-14-93


213 MILE PROFILE 4B
Elevation (m)
Distance (m)
River Flux
07-29-91
11-02-92
04-14-93

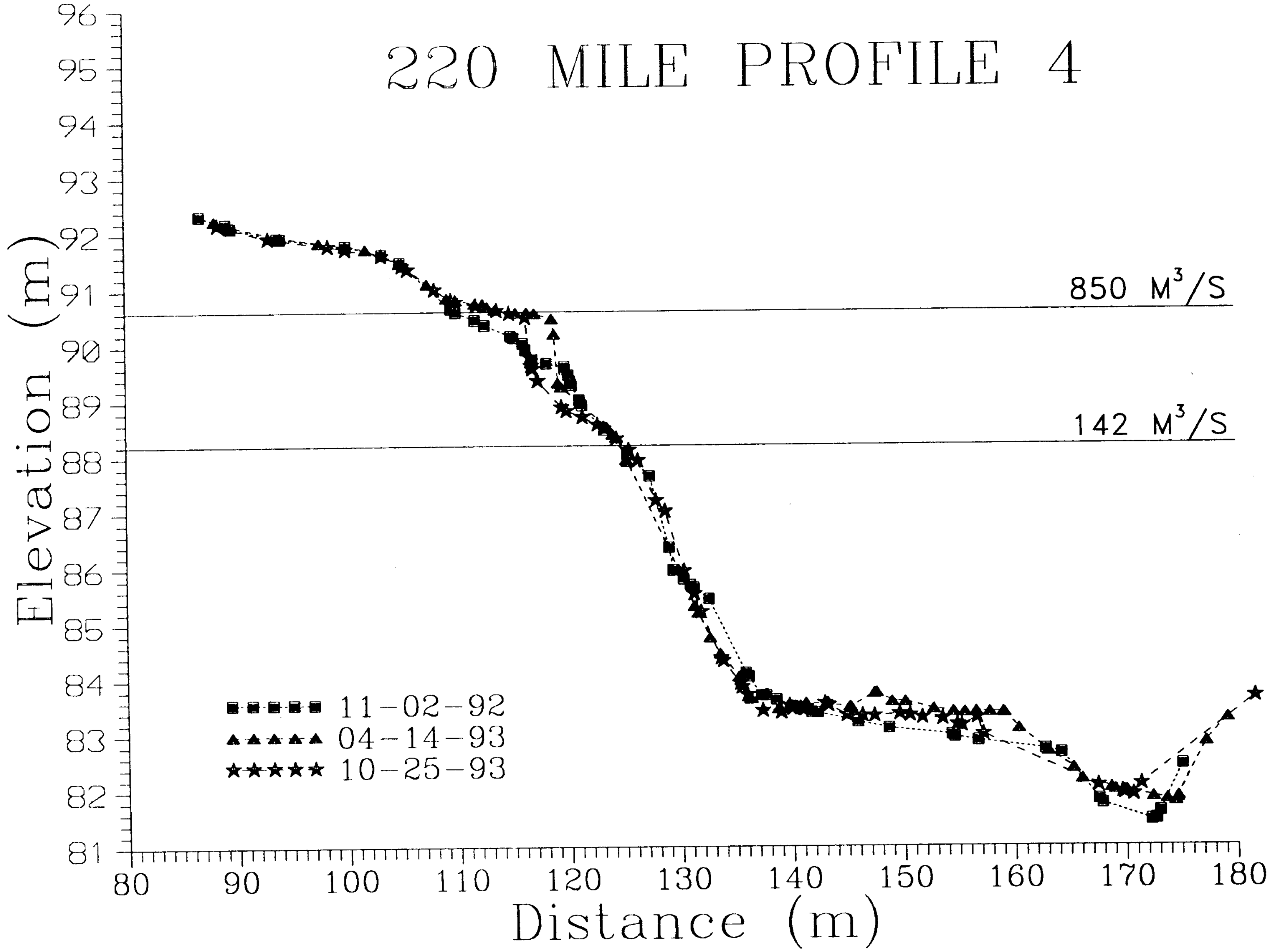

213 MILE PROFILE 5
Elevation (m)
Distance (m)
River Flux
07-29-91
11-02-92
04-14-93

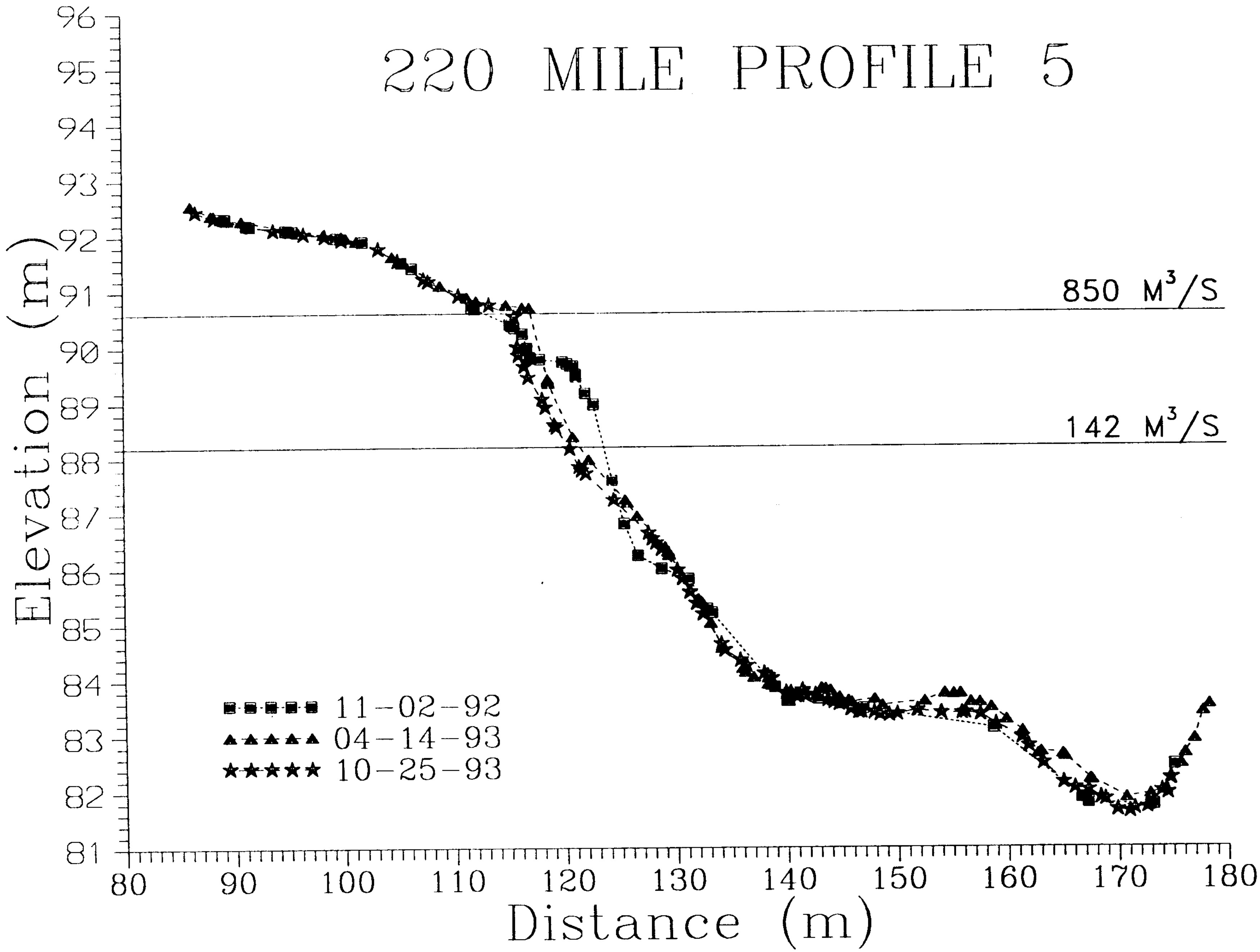

213 MILE
HAZ Volume (m3)
5250
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Julian Days

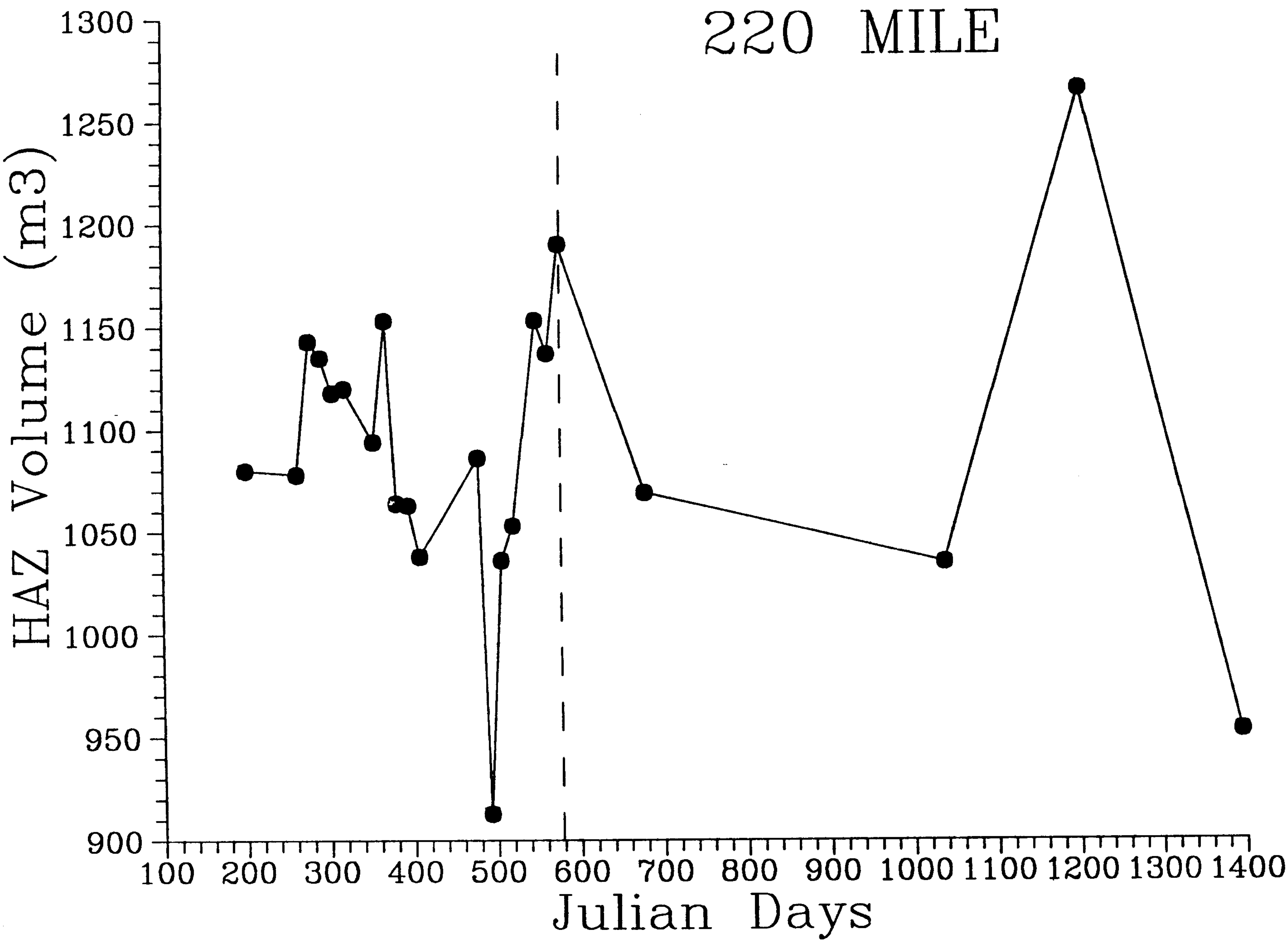

220 R
5-31-94
RM 220.0
Area of Study
N

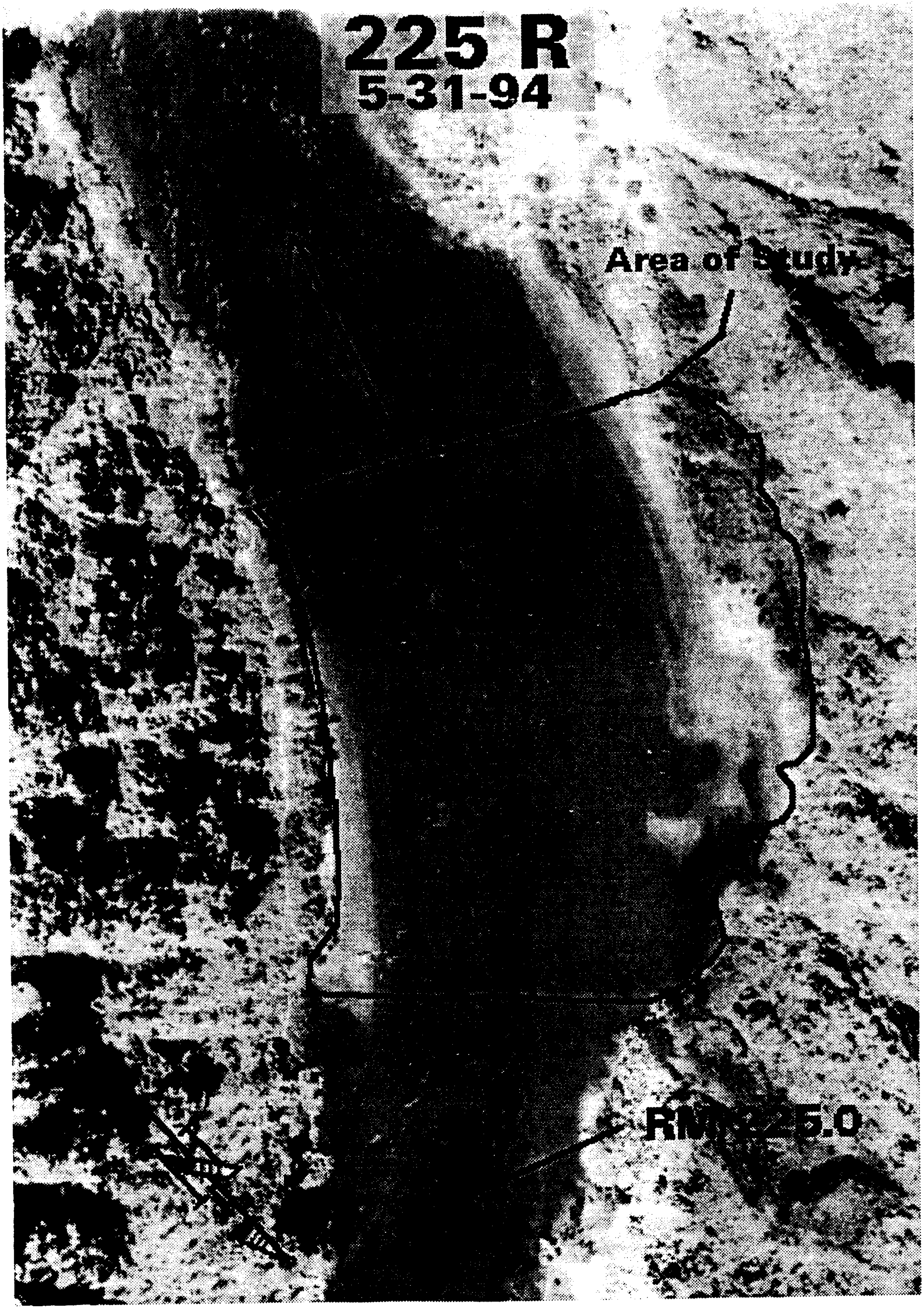


GCES BEACH SURVEY B32 220R-B32 220R 10-25-93 1: 400


220 MILE PROFILE 4
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
11-02-92
04-14-93
10-25-93
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
90
100
110
120
130
140
150
160
170
180


220 MILE PROFILE 5
850 M³/S
142 M³/S
Elevation (m)
Distance (m)
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
90
100
110
120
130
140
150
160
170
180
11-02-92
04-14-93
10-25-93


220 MILE
HAZ Volume (m3)
Julian Days
1300
1250
1200
1150
1100
1050
1000
950
900
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400


225 R
5-31-94
Area of Study
RM 225.0