Comparison of the Number and Area of Backwaters Associated with the Colorado River in Glen, Marble and Grand Canyons, Arizona

by

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Abstract — Backwaters provide important rearing habitat for larval and juvenile native fishes in Marble and Grand canyons. Geomorphology, sediment supply and antecedent flow conditions dictate backwater location, number and size. Size and number of backwaters have important implications for native fish populations.

This study compared the number and area of backwaters greater than 100 m^2 recorded by aerial videography in Glen, Marble and Grand canyons of the Colorado River at 227 cubic meters per second (cms) constant flows during 1990, 1992, 1993 and 1994. Number of backwaters among years was significantly different (G-test, $p<0.025$). Number of backwaters decreased from 146 in 1990 to 70 in 1992. Following winter flooding of the Little Colorado River in January and February 1993, and a concurrent input of sediment, number of backwaters increased to 113 in 1993. Number of backwaters decreased to 89 in 1994. More backwaters occurred in wide reaches than in narrow reaches (G-test, $p<0.025$). Crucial reaches for native fishes are found above and below the Little Colorado River confluence and below the Havasu Creek confluence. Mean area of backwaters during constant 227 cms flows in 1990 (733 m^2), 1992 (450 m^2), 1993 (649 m^2) and 1994 (798 m^2) was not significantly different (Kruskal-Wallis test, $p=0.099$, $n=55$ for each year).

Number of backwaters at 142 and 227 cms flows during 1990 for river kilometers 89.3 to 122.3 were also compared. Significantly more backwaters appeared at the 142 cms discharge level (42) than at the 227 cms level (21) (G-test, $p<0.05$). Mean area of backwaters in 1990 at 227 cms (741 m^2) was greater than those at 142 cms (493 m^2), but was not significantly different (Mann-Whitney test, $p=0.307$).

Keywords: backwaters, Colorado River, Grand Canyon, native fishes.

INTRODUCTION

This report supplements past and ongoing research through the auspices of Glen Canyon Environmental Studies (GCES), Bureau of Reclamation, Flagstaff, Arizona. One aspect of the aquatic studies is addressed in this report: number and area of backwaters during constant flows for 1990, 1992, 1993 and 1994. The study area is comprised of the Colorado River from Glen Canyon Dam through Glen, Marble and Grand canyons to the head of Lake Mead, northern Arizona, river kilometers –24.9 to 447.3 (Figure 1). River kilometer designation is determined by distance from Lees Ferry, river kilometer 0.

Backwaters are important to native fishes in Marble and Grand canyons as rearing habitat [Maddux et al. 1987; Minckley 1991; Angradi et al. 1992; Arizona Game and Fish Department (AGFD) 1993, 1994, 1995]. All the native fish species, bluehead sucker (*Catostomus discobolus*), flannelmouth sucker (*Catostomus latipinnis*), humpback chub (*Gila cypha*) and speckled dace (*Rhinichthys osculus*), were found in backwaters in the study area, except razorback sucker (*Xyrauchen texanus*)[1] (Table 1). Backwaters were shown to be significantly warmer than the Colorado River mainstem in the daytime during the warmer months of the year, late April to October (Angradi et al. 1992; AGFD 1993, 1994, 1995). Larval and juvenile native fishes were more common in areas of warmer water temperature, and were found in backwaters rather than associated with the mainstem face of reattachment bars (AGFD 1993, 1994, 1995). Anderson et al. (1986) determined that backwaters comprised only 2.5% of all river habitats studied, and eddies comprised the highest percentage of river habitats studied, 52.4-59.3%. Backwaters are important for the growth and survival of larval and juvenile native fishes. Eddies are important for adult fish, especially the humpback chub (Valdez et al. 1992).

Backwaters were defined at a meeting of GCES researchers in December 1992 (Riley 1992, Wegner 1992). A backwater in Glen, Marble and Grand canyons is a body of water that exhibits zero to extremely low velocity, and is surrounded on at least three sides by land. Two types of backwaters were identified (Figure 2):

> Type I - backwaters associated with eddy return-current channels and reattachment bars;
>
> Type II - shoreline cavities or pocket waters associated with bank irregularities or channel roughness.

Type I backwaters were identified as backwaters of prime concern in Glen, Marble and Grand canyons because they have greater potential to warm above the ambient temperature of the mainstem Colorado River. Type I backwaters are formed during higher flows when

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[1] Razorback suckers are very rare in Marble and Grand canyons. Only a few adults have been found in this area, and they were not in backwaters. There is currently no known spawning population of razorback suckers in the study area. However, larval and young-of-year razorback suckers are known to utilize backwaters in the Upper Colorado River Basin.

reattachment bars are formed or reformed and sediment is deposited during receding flows. A backwater, by definition, appears or exists when the reattachment bar is exposed and the associated return-current channel contains water. [Refer to Ruben et al. (1990), Schmidt (1990) and Schmidt and Graf (1990) for detailed discussions on sediment in Grand Canyon and backwater formation.] There are two forms of Type I backwaters: connected backwaters and isolated backwaters. Connected backwaters are those that have an open connection between the mouth of the backwater and the mainstem. Isolated backwaters are backwaters that become completely separated from the flow of the mainstem when river stage drops. Under current, normal dam operations, daily low fluctuating flows, these isolated backwaters are isolated for intermittent periods of time and can be reconnected to the mainstem when river stage increases.

METHODS

To obtain aerial videography, a video camera was attached to the underside of a helicopter and images were routed to a monitor viewed by an onboard observer. Narration by the observer included location along the river corridor as the helicopter flew the length of the study area at 2,000 feet above the river. Videotapes used were ¾ inch wide and 20 minutes in recording length.

Research flows, as measured from the turbines of Glen Canyon Dam (Appendices I-III), and dates of the videotapes examined included:

- 142 cubic meters per second (cms) constant [5,000 cubic feet per second (cfs)], September 30, 1990,
- 227 cms constant (8,000 cfs), October 15, 23-24, 1990,
- 227 cms constant, October 11-12, 1992,
- 227 cms constant, May 30-31, 1993,
- 227 cms constant, May 30-31, 1994.

The entire study area was included in the analysis of backwaters during 227 cms constant flows. For comparison of the 142 and 227 cms constant flows during 1990, the study area was restricted to RKM 89.3 to RKM 122.3. This was because the videotapes of the 142 cms constant flows only covered this reach. There were no other 142 cms constant flows on videotape to make a reliable comparison to 227 cms constant flows.

Videotapes were analyzed using a 486-66, 16 megabyte RAM microcomputer system and the Map and Image Processing System 3.30 (MIPS) software package by MicroImages, Inc. Video images were viewed on a color monitor and captured when a backwater came into view.

Type I backwaters greater than or equal to 100 square meters (m^2) were included in the analyses. Information obtained from the videos included number, area (m^2), and location (river kilometer and side) of backwaters. Location of a backwater was indicated as river kilometer to the nearest tenth from Lees Ferry using the river guide by Stevens (1983). River kilometer location was also marked left or right as determined when facing downstream. Number of backwaters for each year studied were examined by river reach (Table 2). River reaches are based on geomorphology (Schmidt and Graf 1990).

To measure area of backwaters, a raster was constructed to calibrate the measuring tools (caliper and planimeter functions). Scale was calculated by registering the raster to USGS topographic maps (Weiss 1993). Ground truthing was performed by Weiss to verify scale. Calculated measurements deviated no more than 10% from real surface area values.

Isolated backwaters are isolated for intermittent periods and might still be useful habitat for fishes, hence they were included in the analyses. River flows fluctuate on a daily basis under normal operations. These steady research flows were short-term. These isolated backwaters comprised a small percentage of the total number of backwaters; 6%, 10%, 11.5% and 16.8% for 1990, 1992, 1993 and 1994, respectively.

Statistical analysis included the use of the G-test (Sokal and Rohlf 1981) for comparison of the number of backwaters during 227 cms constant flows for 1990 through 1994, and for comparison of the number of backwaters in narrow reaches versus wide reaches. The G-test was also used for comparison of the number of backwaters between 142 cms and 227 cms constant flows in 1990.

Statistical analysis of backwater area for the 227 cms constant flows was accomplished by taking a subsample from the population of backwaters counted and measured for each study year. Subsamples were randomly chosen by first assigning a number to each backwater, then generating a table of random numbers on the computer. The first 55 generated numbers and corresponding backwaters were chosen, without replacement, for each study year. The Kruskal-Wallis test (Sokal and Rohlf 1981) was used to analyze the 227 cms steady flow data due to nonnormality and dependence of backwaters among reaches and between years. The Mann-Whitney U-test (Sokal and Rohlf 1981) was used to statistically analyze area between 142 cms and 227 cms steady flows by using all data points for each flow regime.

RESULTS

Number of Backwaters at 227 cms Constant Flows Over Time

There was a significant difference in the number of backwaters among years (G-test, $p<0.025$). Backwater numbers decreased between 1990 (146) and 1992 (70), increased in 1993 (113), and decreased in 1994 (89) (Figure 3, Table 3). Also, the greatest number of backwaters occurred in wide reaches over narrow reaches (G-test, $p<0.025$), particularly reaches 4 and 10 (Tables 2 and 3).

The 1990 videography stopped at the beginning of reach number 12 (RKM 378.1); however, it is possible there were a few backwaters in that last reach. Also, a segment of videotape was of poor quality (RKM 350.8-372.5). This missing segment of data represents the river in a narrow reach, and there were likely a few, not many, backwaters in this reach of the river that were missed. Although the number of backwaters in 1990 was likely underestimated, 1990 had the highest number of backwaters among all years studied.

Number of Backwaters at 142 and 227 cms Constant Flows

During 1990, for the reach from RKM 89.3 to RKM 122.3, there were significantly more backwaters at the 142 cms discharge level than at the 227 cms level (G-test, $p<0.05$). There were 42 backwaters at 142 cms constant discharge and 21 backwaters at 227 cms constant discharge (Table 4).

Area of Backwaters

Mean area of backwaters during 227 cms constant flows in 1990 (733 m^2, n=55), 1992 (450 m^2, n=55), 1993 (649 m^2, n=55) and 1994 (798 m^2, n=55) was not significantly different (Figure 4) (Kruskal-Wallis H=6.269, p=0.099). In 1990, mean area of backwaters from RKM 89.3 - 122.3 during 142 cms flows (493 m^2, n=42) was not significantly different from the mean area of backwaters during 227 cms flows (741 m^2, n=21) (Figure 5) (Mann-Whitney U=371, p=0.307).

REVIEW OF WEISS (1993) BACKWATER DATA

Weiss (1993) examined videotapes to determine the number of backwaters from Glen Canyon Dam to Lake Mead at low and high flows. Flows (Appendices II and III) and dates of videography examined, as reported by Weiss, included:

- 793 cms constant (28,000 cfs), May 15-16, 1985,
- 136 cms constant (4,800 cfs), October 20-22, 1985,
- 425 cms constant (15,000 cfs), May 20-22, 1991,
- 142 cms constant (5,000 cfs), July 27-28, 1991.

During 1985, actual flows differ from those reported by Weiss (1993). Discharges from the dam during May 15-16, 1985, were actually 708 cms (25,000 cfs). Discharges during the entire month of October, 1985, were fluctuating flows under standard operations, not steady flows

(Bureau of Reclamation files, Appendix III). Caution should be used when interpreting the information during the October, 1985, discharges. The mean discharge release of these fluctuating flows for October, 1985, was between 311 and 368 cms (11,000 and 13,000 cfs), which is below the high steady discharges of 708 cms (25,000 cfs) for May, 1985.

Weiss determined that there were more backwaters at lower flows than at high flows. During 1985, there were 568 backwaters at the lower flow levels and 188 backwaters at the higher flow levels (Table 5). During 1991, there were 114 backwaters at the 142 cms level and 46 backwaters at the 425 cms level (Table 5). The low flow scenarios for both 1985 and 1991 occurred after high research flows within each study year. The high flows likely contributed to the formation of the backwaters that appeared at the lower flows. Thus the number of backwaters at the lower flows could be somewhat inflated when making comparisons to the higher flows. For all flows there are more backwaters in wide reaches than narrow reaches of the river during 1985 (Figure 6) and 1991 (Figure 7).

Sustained high volume releases from Glen Canyon Dam occurred from 1983-1986 due to large inflow volumes from the Upper Colorado River Basin (Appendix I). These high flows redistributed sediments from the riverbed to sandbars and river margins resulting in an increase in the number of backwaters after flooding subsided. After the flooding events, erosional processes in the study area continued, accounting for the lower number of backwaters in subsequent years. This would account for the extremely high numbers of backwaters in 1985 over 1991. Kearsley et al. (1994) reported that the flood events of 1983-1986 aggraded sandbars system wide, but eroded some sandbars in narrow reaches. They also report that sandbars eroded after the 1983-1986 floods and continued up to 1991, the end of their study period.

Mean area of backwaters for 1991 flows of 142 and 425 cms was only slightly different, 630 and 737 m^2, respectively (Figure 8). Area of backwaters from the 1985 videos was not measured due to the use of videotapes not compatible with the videocassette player used with the MIPS computer system.

DISCUSSION

Number of Backwaters at 227 cms Constant Flows Over Time

The decrease in number of backwaters from 1990 to 1992 could be accounted for by the erosional processes that occurred in the study area. [See Schmidt and Graf (1990) and Cluer and Dexter (1994) for detailed information on Glen, Marble and Grand canyon erosional and depositional processes of sediment.] Sediment input into the canyon system was limited, thus aggradation to sand bars was nominal. Kearsley et al. (1994) reported a system wide decrease in the size and number of alluvial sand deposits in Grand Canyon from 1965 to 1991. However, there was a short-lived increase in number and size of sand deposits after flood events in 1983.

The pivotal point in the change of backwater numbers among years studied was the input of water and sediment from the January and February, 1993, flooding of the Little Colorado River (LCR). Floods tend to scour return-current channels and aggrade sandbars (AGFD observations, Schmidt and Graf 1990, Beus et al. 1994). However, clear water floods can also aggrade sandbars by redistributing stored riverbed sand, as was seen from the 1983 flood flows (Kearsley et al. 1994).

The 1993 winter floods of the LCR accounted for the increase in the number of backwaters in 1993. These LCR floods brought high sediment loads and increased flow into the Colorado River for a short time. Flow of the Colorado River increased to 850 cms below the confluence with the LCR. New backwaters were formed and existing sandbars were reformed or aggraded (Beus et al. 1994, Cluer and Dexter 1994).

Visual observation of backwaters on videotape indicated that during 227 cms constant flows in 1993, some reattachment bars were barely inundated by water. In previously viewed videos from 1990 and 1992, these same reattachment bars were exposed. This inundation of reattachment bars could be attributed to the loss of sediment. Another possibility could be that flows from tributaries were higher than during previous videography and contributed to an increase in river stage, thus inundating reattachment bars. There is considerable variability in the system, thus determining the cause of differences is extremely difficult. In any event, there were more backwaters in 1993 than in 1992 even with the inundation of the same few reattachment bars in 1993.

Further observation of 1993 videos suggested there was a substantial amount of additional sediment in the system deposited on terraced sediment deposits, separation and reattachment sandbars, or in channel margins. There were many new small (< 100 m^2) backwaters, mostly located in the downstream reaches of the study area, particularly reach number twelve. These smaller backwaters were not included in the analyses for this report.

The decrease in the number of backwaters from 1993 to 1994 is attributed to loss of sediment from sandbars. Beus et al. (1994) and Cluer and Dexter (1994) reported a measured increase in sandbars in the study area after 1993 floods, then an initial rapid and continuing loss of sediment from the sandbars. Observations by AGFD fishery researchers indicated that much of the sediment deposited by the LCR floods of 1993 was composed of fine, easily erodible material. There were no high flows in the system since the 1993 floods to aggrade sandbars. Further observation of the 1994 videotapes indicated that the many, new, small, backwaters in the lower reaches of the river observed in 1993 no longer existed in 1994; the sandbars were no longer evident. Additionally, there appeared to have been a very large amount of sediment in the river channel at the inflow to Lake Mead. However, the mean elevation of Lake Mead was 8.7 feet lower during the month of May in 1994 than in 1993 (Bureau of Reclamation files), thus possibly giving an impression of more accumulated sediment in this area than actually existed.

General Discussion

Backwaters are important to all native fish species of the Colorado River in Marble and Grand canyons. Other habitats that may be important to larval and juvenile fishes are channel margins and cobble riffles. These other habitats have not been quantified to date, but are worthy of investigation. Crucial reaches for native fishes in the study area are reaches 4 and 5 (bracketing the LCR confluence), and 10 (below the Havasu Creek confluence) (Table 3). These are reaches with the greatest numbers of backwaters and greater catch rates of native fishes. In particular, backwaters located in reach 5 (RKM 99.0-124.5), just below the LCR, are very important to the survival of the humpback chub, an endangered species, that spawns in the LCR. Humpback chub was found mostly in reach 5 (AGFD 1994, 1995). The highest catch rates of bluehead sucker, flannelmouth sucker and speckled dace occurred in reach 10, followed by reach 5 (AGFD 1994, 1995).

Due to spawning activity by humpback chub in the mainstem, backwaters located in reaches 4 (RKM 57.9-99.0) and 10 (RKM 257.4-344.0) are also particularly important. There is evidence that adult humpback chub spawned during 1993 near RKM 49.4 (reach 4) and somewhere in reach 9 (RKM 225.3-257.4) or 10 (RKM 257.4-344.0); larval fishes were found near RKM 70.8 and 328.2 (AGFD 1994). During April, 1994, AGFD found two individual chubs (29 and 41 mm total length) near RKM 70.8 and one individual chub (43 mm total length) near RKM 94.4. These individuals were suspected to be from the 1993 cohort spawned in the mainstem (AGFD 1995). However, recruitment of these fish into the adult spawning population has not been documented. Also, on July 14, 1994, BIO/WEST documented larval fish (24 mm mean total length) in the mainstem at a spring source at RKM 49.4, indicating humpback chub spawned in the mainstem during 1994 (Valdez and Masslich 1994).

The quantity of backwaters alone does not give a complete picture of the importance of backwaters as native fish rearing habitat. Quality of backwaters, such as food availability, water temperature and refugia potential, is important for fish growth and survival. AGFD (1994, 1995) has shown that backwaters contain more zooplankton, benthic invertebrates and detritus than the mainstem along associated reattachment bars. Also, the temperature of backwaters is significantly warmer than the mainstem. Larval and juvenile fishes are found in these backwaters rather than in the mainstem (Angradi et al. 1992; AGFD 1993, 1994, 1995).

Glen Canyon Dam is currently operated under interim operations. Interim flows were initiated August 1, 1991, and officially implemented by the Secretary of the Interior on November 1, 1991. Allowable minimum discharges from Glen Canyon Dam are currently 142 cms during the night, and 227 cms from 7 am to 7 pm. Allowable maximum discharges are 566 cms. Prior to interim operations, standard operations of the dam were to fluctuate flows daily on a wider scale. The range of flows reached a low of 28 or 85 cms, depending on the time of year, and the regulated high discharge was 892 cms (Bureau of Reclamation 1995). Exceptions occurred during the consistent high flows of 1983-1986, and during the lower, periodic, steady, research flows from 1990 through 1994 (Appendix I).

Fluctuating flows disrupt backwater habitats (Kennedy 1979, Angradi et al. 1992). Ascending flows can flush backwaters causing a drop in water temperature and loss of food items. Descending flows can isolate or dewater backwaters thus reducing available habitat. However, since implementation of interim operations, backwater habitats for fish downstream of Glen Canyon Dam have improved somewhat, although conditions are not considered optimal (AGFD 1994). A preliminary study of water quality indicated that water temperature of backwaters and the mainstem will warm during steady flows (Hoffnagle, in preparation). Under steady flows or flows of extremely limited fluctuations, food production sites may become more reliable, water temperature may become more accommodating, and growth and survival of fishes may increase.

Backwater location, number and size has been largely influenced by the presence of Glen Canyon Dam, the historical flow regime of water released from the dam, the geomorphology of the canyons, and sediment supply. The number of backwaters varies over time and at different flow stages. However, based on this report and Weiss (1993), greater numbers of backwaters appear at lower flows. As river stage increases, low velocity areas become inundated and may revert to eddies (Schmidt and Graf 1990). AGFD (1994) found greater numbers of fish in backwaters of larger surface area and greater perimeter.

It is likely that backwaters will tend to fill and reattachment sandbars that define backwaters will continue to erode under interim operations. Beus et al. (1994) reported that interim operations have not reduced erosion rates of sandbars in Grand Canyon, but have increased sediment retention in the riverbed. Cluer and Dexter (1994) reported that erosion and deposition of sandbars is a phenomenon that is highly dynamic and cyclic. A sandbar can exhibit erosion and deposition cycles several times a year. A sandbar changes in size, increasing or decreasing, during these cyclic events. Each time sediment is eroded from a sandbar, it has the potential to be carried downstream. Cluer and Dexter (1994) showed that the overall, average change in sandbars studied from 1991 through 1993 was a 5% reduction in area. With controlled flood flows, such as the habitat maintenance flows proposed in the Glen Canyon Dam Final Environmental Impact Statement (Bureau of Reclamation 1995), it may be possible to maintain and reform backwaters. High flows can scour return-current channels and redistribute stored riverbed sediment to sandbars.

RECOMMENDATIONS

To aggrade sandbars and maintain backwaters in Glen, Marble and Grand canyons, controlled flood flows should be implemented. These controlled floods could be habitat maintenance flows as described in the Glen Canyon Dam Final Environmental Impact Statement (Bureau of Reclamation 1995). The flood flows should be implemented during the spring in years when stored sediment is plentiful and a strong year class of humpback chub is not evident. Habitat maintenance flows of 850 cms could be beneficial by evidence of the LCR flood flows during the winter of 1993. Clear flood flows also can aggrade sandbars by redistributing stored riverbed sand (Kearsley et al. 1994). A question remains as to the effects of sustained high flows on the reaches of the Colorado River above the confluence with the LCR. These upper reaches are susceptible to a reduction of riverbed sand over time due to a lack of sediment input in these reaches. It is recommended that experimental flood flows of 850 cms be implemented for one to two weeks during springtime (year to be determined) to further evaluate the effects on maintaining and reforming backwaters. Upon completion and evaluation of these controlled flood flows, higher controlled flood flows could be considered. Such determinations would be handled through the Adaptive Management process (Bureau of Reclamation 1995).

Due to the crucial nature of backwaters as native fish rearing habitat, flows should allow for the greatest number of available backwaters. Fluctuating flows disrupt backwater habitat (Kennedy 1979, Angradi et al. 1992), therefore fluctuating flows should be minimized. Since indication of mainstem spawning by humpback chub in 1993 and 1994 has occurred under low fluctuating flows, it can be inferred that low, steady flows may also improve conditions for mainstem spawning of adult native fishes and survival of fish eggs. Low, steady flows of 142 cms during the fish spawning and rearing periods of late April to October are recommended. Low flows should be steady or, if needed, could fluctuate between the 142 and 227 cms discharge levels. Low or moderate fluctuating flows, as described in the Glen Canyon Dam Final Environmental Impact Statement (Bureau of Reclamation 1995), could be implemented during the other months of the year.

The GCES office plans another videography flight over the Memorial Day weekend this year during another 227 cms constant, research flow period. It is recommended that monitoring of changes in backwaters be continued by this method.

ACKNOWLEDGEMENTS

Thanks are extended to GCES personnel for use of their services and equipment. Special thanks go to Valerie Saylor for providing the sketches in Figures 1 and 2, and to Bill Vernieu for providing the hydrographs in the appendices. Special thanks also go to the people in the Research Branch, AGFD, and to Larry Riley, Habitat Branch, AGFD, for their encouragement and assistance.

Table 1. Native fish species recently found in the Colorado River through Glen, Marble and Grand canyons.

SCIENTIFIC NAME	COMMON NAME
Catostomus discobolus	bluehead sucker
Catostomus latipinnis	flannelmouth sucker
Gila cypha	humpback chub
Rhinichthys osculus	speckled dace
Xyrauchen texanus	razorback sucker

Table 2. Geomorphic reaches within Glen, Marble and Grand canyons (Schmidt and Graf 1990, Bureau of Reclamation 1995).

REACH NUMBER	KILOMETER DELINEATION	REACH NAME	WIDTH DESIGNATION
0	-24.9 - 0	Glen Canyon	wide
1	0 - 18.2	Permian Section	wide
2	18.2 - 36.4	Supai Gorge	narrow
3	36.4 - 57.9	Redwall Gorge	narrow
4	57.9 - 99.0	Lower Marble Canyon	wide
5	99.0 - 124.5	Furnace Flats	wide
6	124.5 - 189.5	Upper Granite Gorge	narrow
7	189.5 - 201.9	Aisles	narrow
8	201.9 - 225.3	Middle Granite Gorge	narrow
9	225.3 - 257.4	Muav Gorge	narrow
10	257.4 - 344.0	Lower Canyon	wide
11	344.0 - 379.7	Lower Granite Gorge	narrow
12	379.7 - 447.3	Lake Mead	wide

Table 3. Total number of backwaters, in the Colorado River through Glen, Marble and Grand canyons, by reach at 227 cms (8,000 cfs) constant flows during 1990, 1992, 1993 and 1994.

REACH		NUMBER OF BACKWATERS			
Number	RKM	1990	1992	1993	1994
0	-24.9 - 0	11	5	8	11
1	0 - 18.2	2	4	3	4
2	18.2 - 36.4	3	2	1	0
3	36.4 - 57.9	7	1	0	1
4	57.9 - 99.0	47	16	22	20
5	99.0 - 124.5	8	4	10	11
6	124.5 - 189.5	4	3	8	4
7	189.5 - 201.9	6	0	2	1
8	201.9 - 225.3	2	2	3	3
9	225.3 - 257.4	0	0	0	0
10	257.4 - 344.0	52	25	29	17
11	344.0 - 379.7	4	3	5	2
12	379.7 - 447.3	0	5	22	15
TOTAL		146	70	113	89

Table 4. Total number of backwaters at two different flows in 1990. Constant flows of 142 cms (5,000 cfs) occurred on September 30, 1990. Constant flows of 227 cms (8,000 cfs) occurred on October 23, 1990. For both flow regimes, river kilometers 89.3 through 122.3 were compared.

1990	142 cms	227 cms
No. of Backwaters (G-test, $p<0.05$)	42	21
Total Area	20,693 m^2	15,565 m^2
Mean Area	493 m^2	741 m^2
Standard Deviation	604 m^2	1,059 m^2

Table 5. Total number of backwaters, in the Colorado River through Glen, Marble and Grand canyons, by reach at 136 and 793 cms (4,800 and 28,000 cfs) flows during 1985 and at 142 and 425 cms (5,000 and 15,000 cfs) during 1991. (Information from Weiss 1993.)

REACH		1985		1991	
Number	RKM	136 cms	793 cms	142 cms	425 cms
0	-24.9 - 0	21	1	1	5
1	0 - 18.2	4	1	0	0
2	18.2 - 36.4	10	1	2	2
3	36.4 - 57.9	13	1	9	1
4	57.9 - 99.0	95	24	40	16
5	99.0 - 124.5	79	3	12	1
6	124.5 - 189.5	56	4	3	0
7	189.5 - 201.9	11	3	7	0
8	201.9 - 225.3	13	6	0	1
9	225.3 - 257.4	7	11	1	0
10	257.4 - 344.0	211	114	26	19
11	344.0 - 379.7	48	19	0	1
12	379.7 - 447.3	0	0	13	0
TOTAL		568	188	114	46

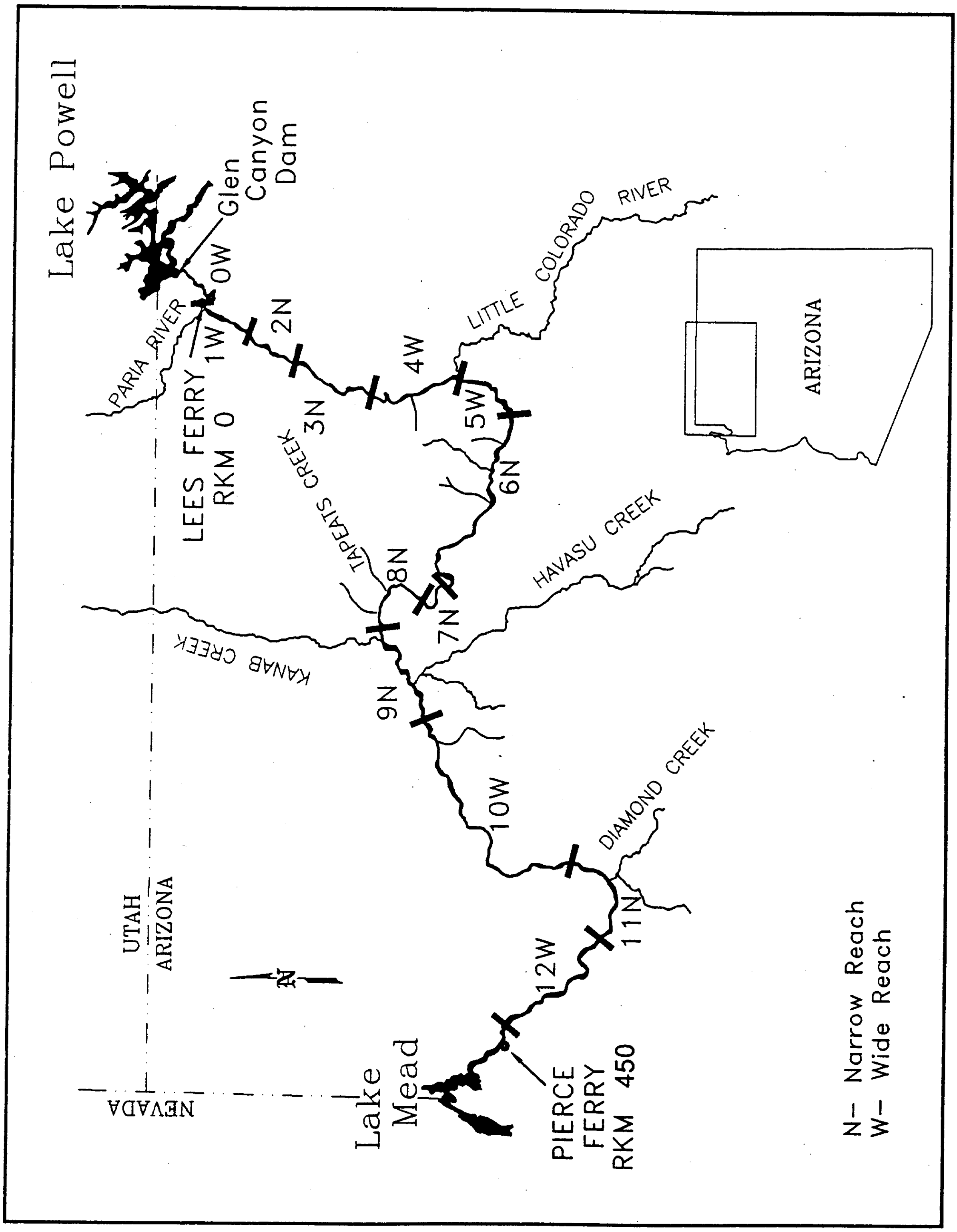

Figure 1. Study area of the Colorado River extending from Glen Canyon Dam to Lake Mead. River reaches are delineated. (Provided by Glen Canyon Environmental Studies, Bureau of Reclamation, Flagstaff, Arizona.)

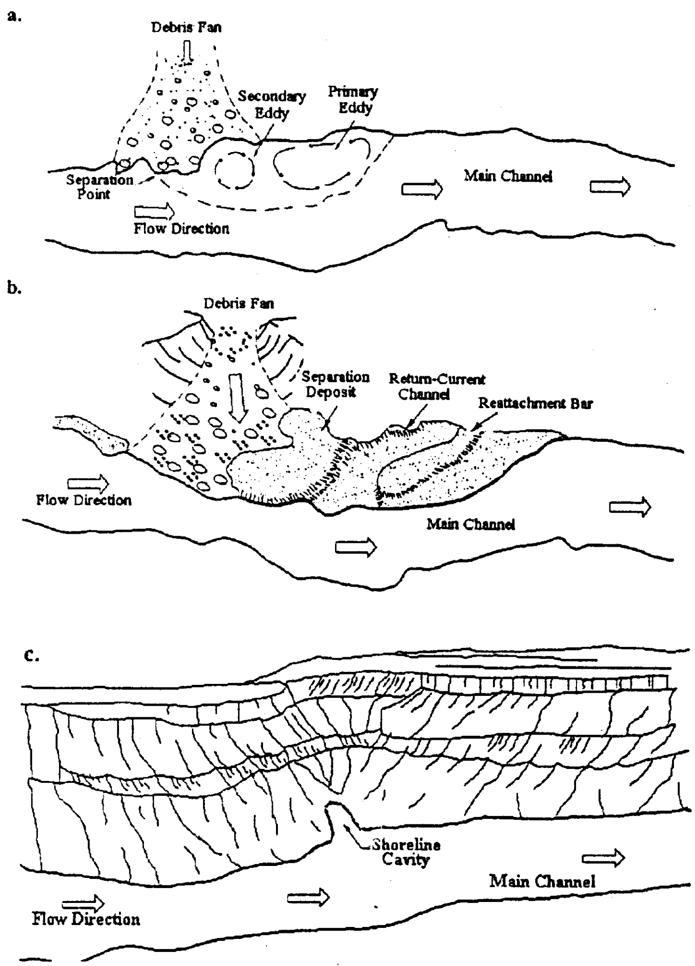

Figure 2. The Type I backwater is illustrated in sketches a and **b** (adapted from Schmidt and Graf 1990). Sketch **a** shows the eddies. Sketch **b** shows the return-current channel that is formed between the primary and secondary eddies. Associated sandbars are included. A Type II backwater is illustrated in sketch **c**. (Sketches provided by Glen Canyon Environmental Studies, Bureau of Reclamation, Flagstaff, Arizona.)

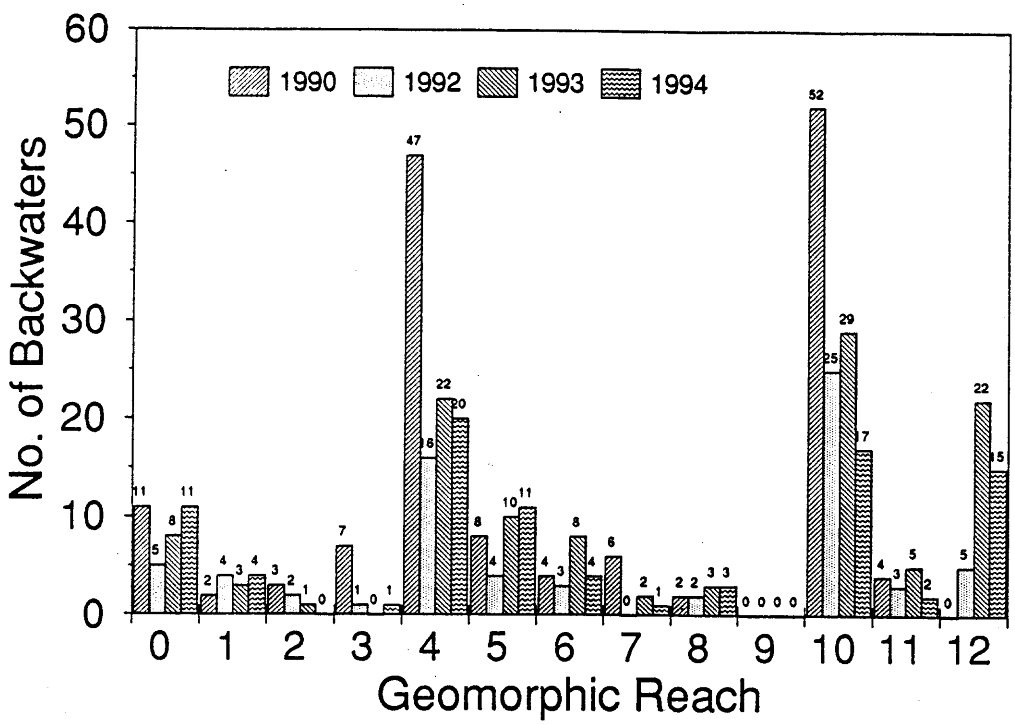

Figure 3. Number of backwaters by reach during 227 cms (8,000 cfs) constant flows in 1990, 1992, 1993 and 1994 (G-test, $p<0.025$).

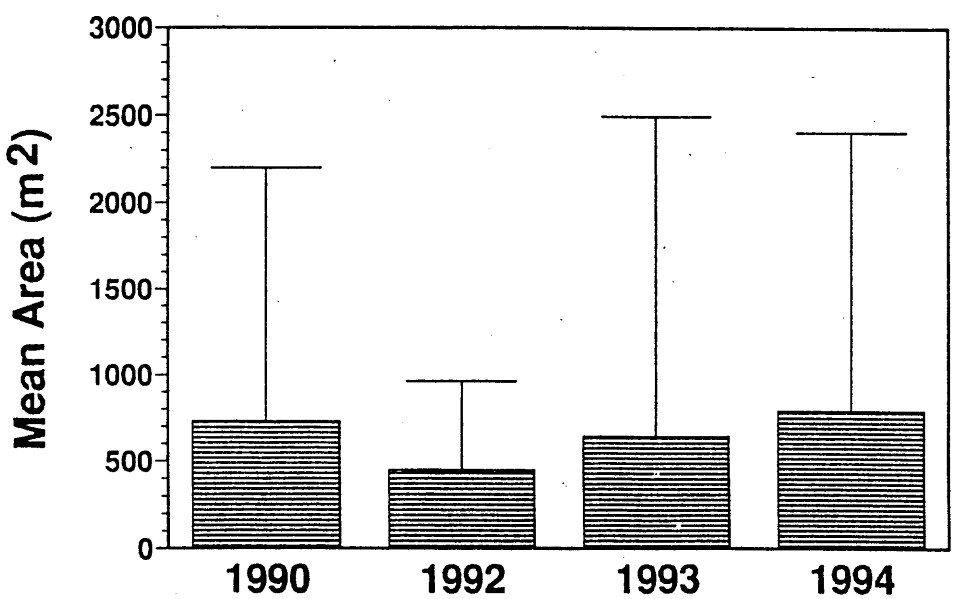

Figure 4. Mean area and standard deviation of backwaters during 227 cms (8,000 cfs) constant flows in 1990, 1992, 1993, and 1994 (Kruskal-Wallis test, $p=0.099$).

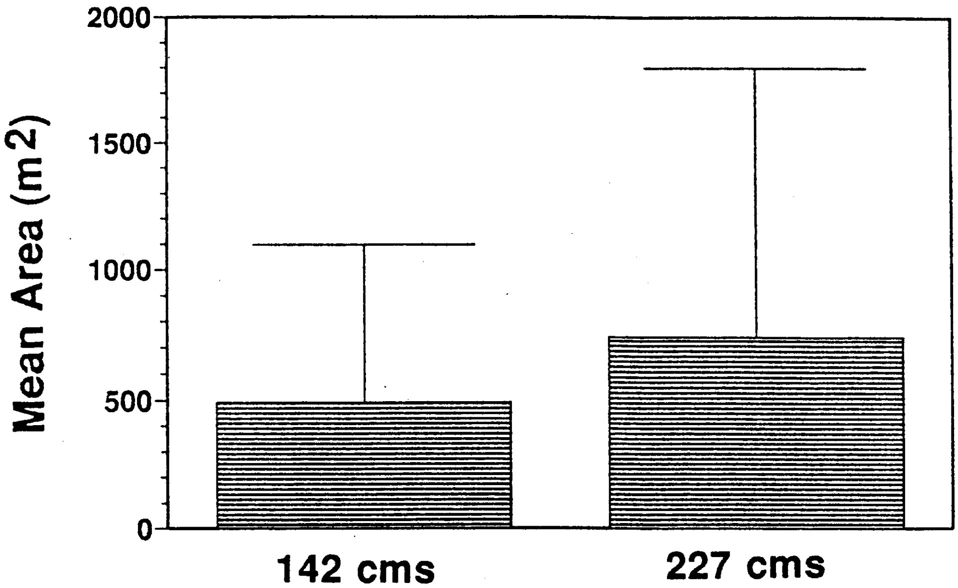

Figure 5. Mean area and standard deviation of backwaters between RKM 89.3-122.3 during 142 and 227 cms (5,000 and 8,000 cfs) constant flows in 1990 (Mann-Whitney test, p=0.307).

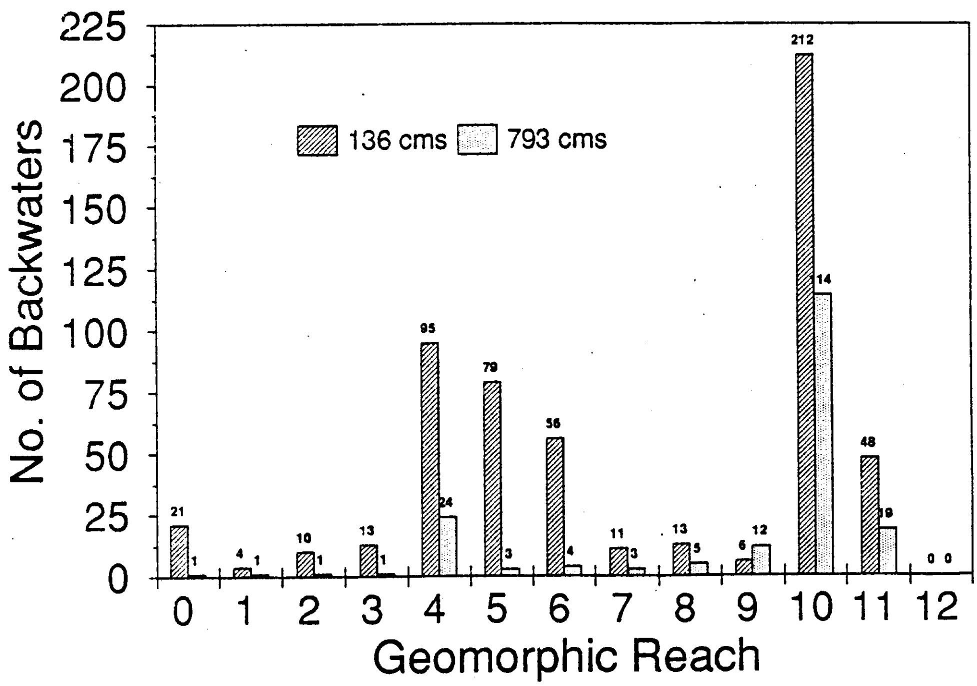

Figure 6. Number of backwaters by reach during 1985 flows (Weiss 1993).

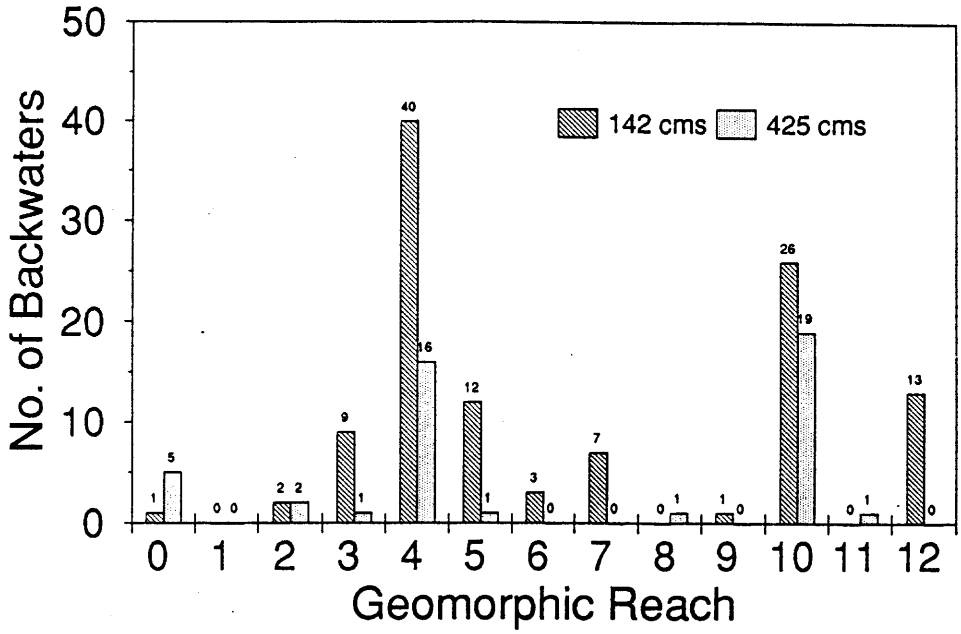

Figure 7. Number of backwaters by reach during 142 and 425 cms (5,000 and 15,000 cfs) constant flows in 1991 (Weiss 1993).

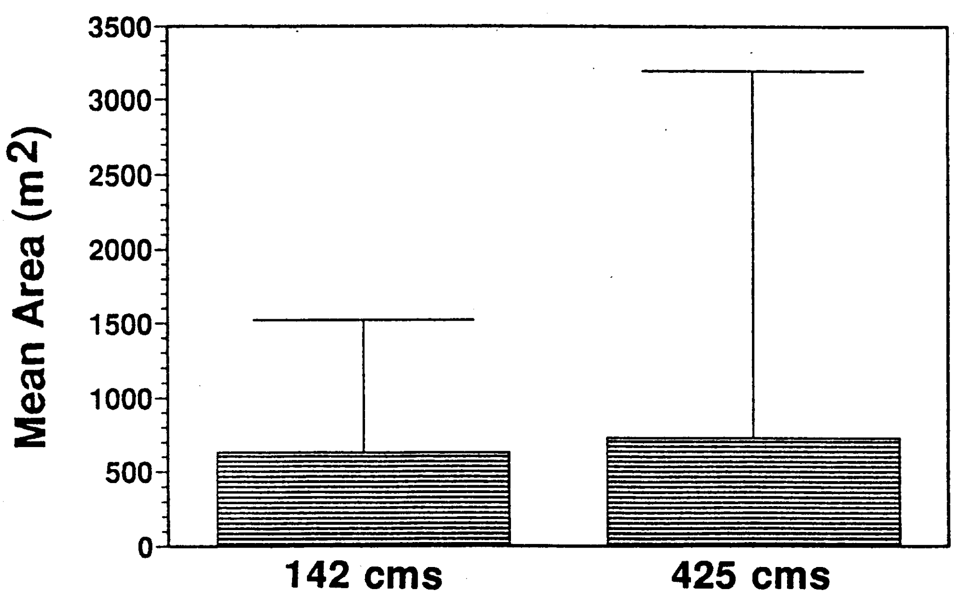

Figure 8. Mean area and standard deviation of backwaters during 142 and 425 cms (5,000 and 15,000 cfs) constant flows in 1991 (Weiss 1993).

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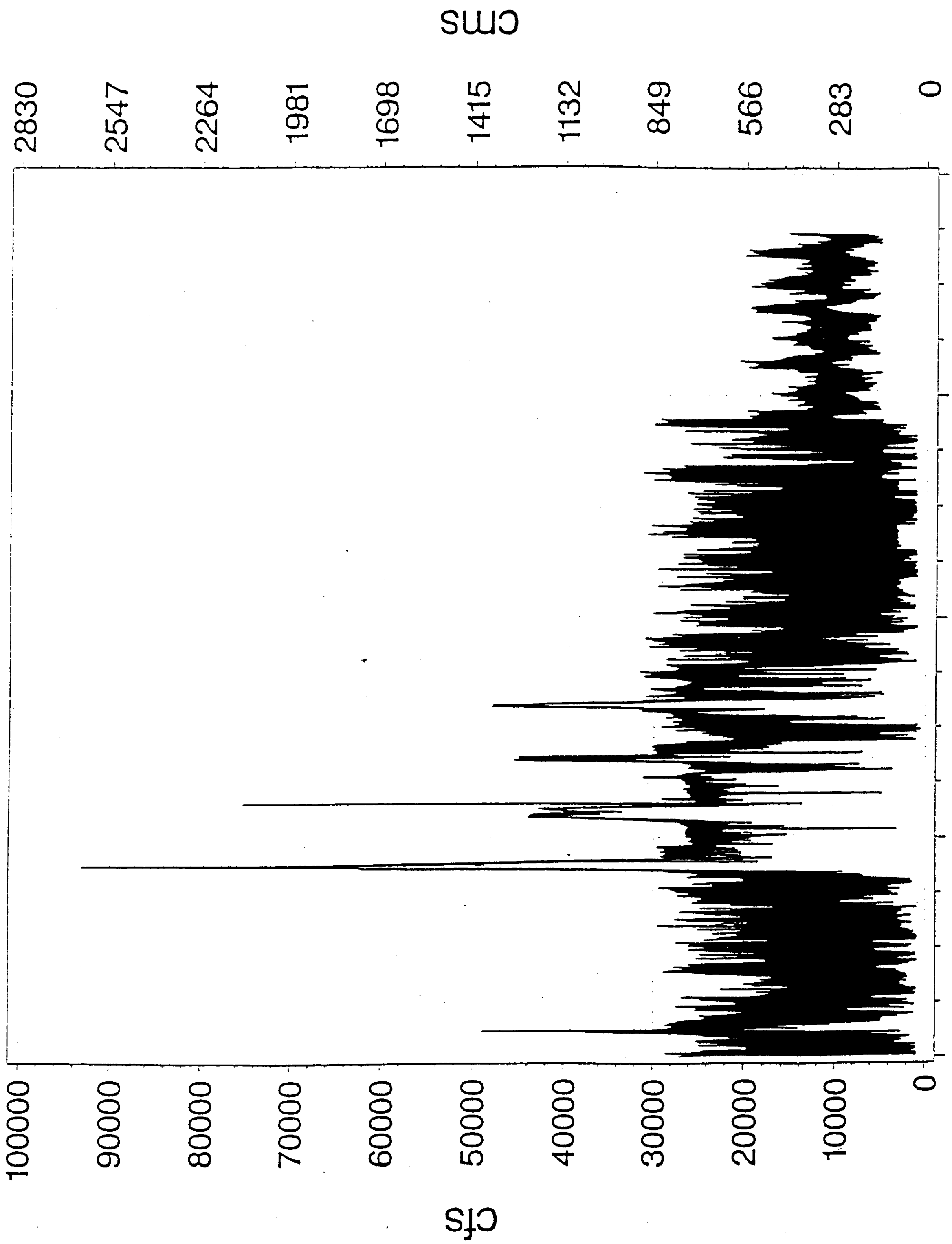
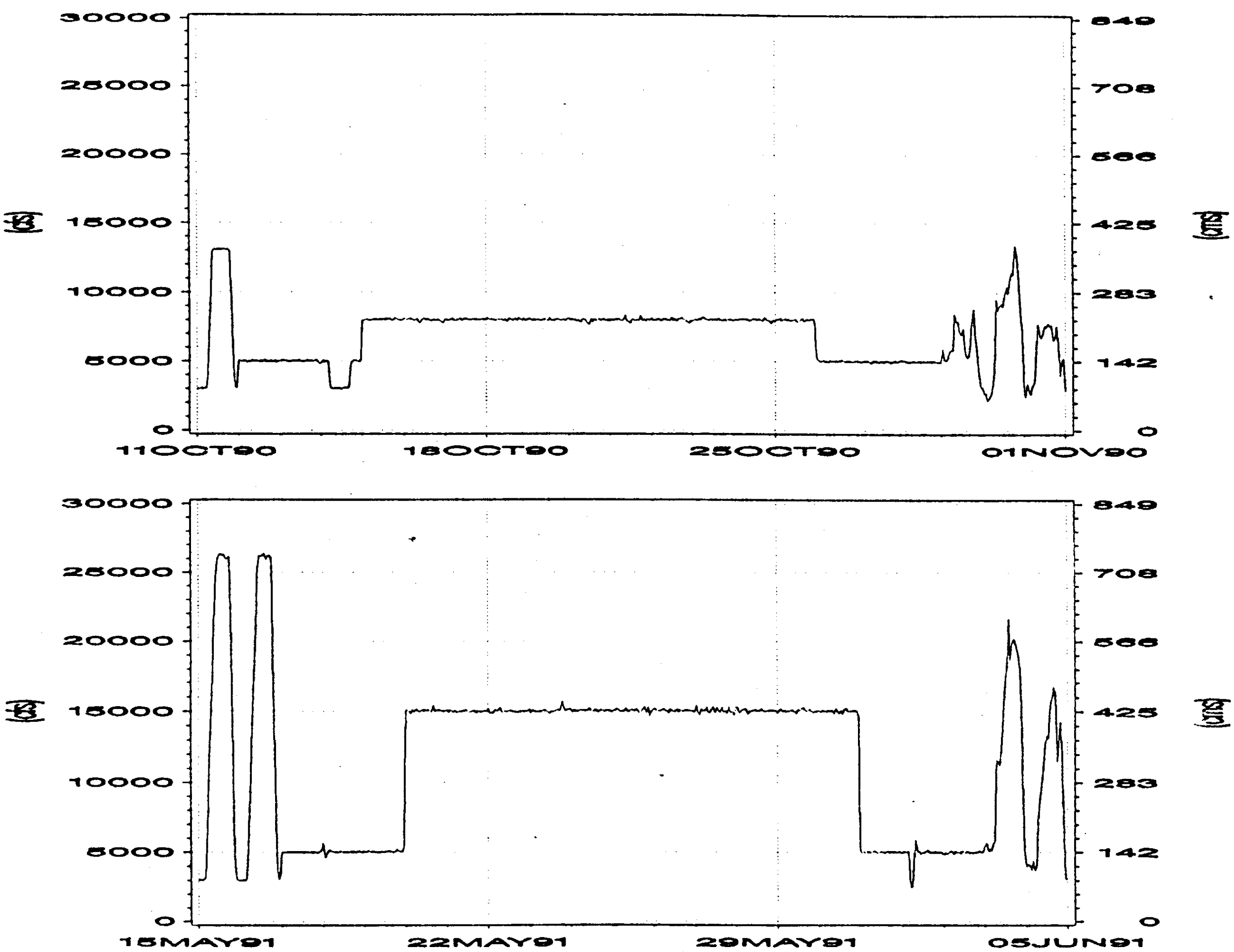
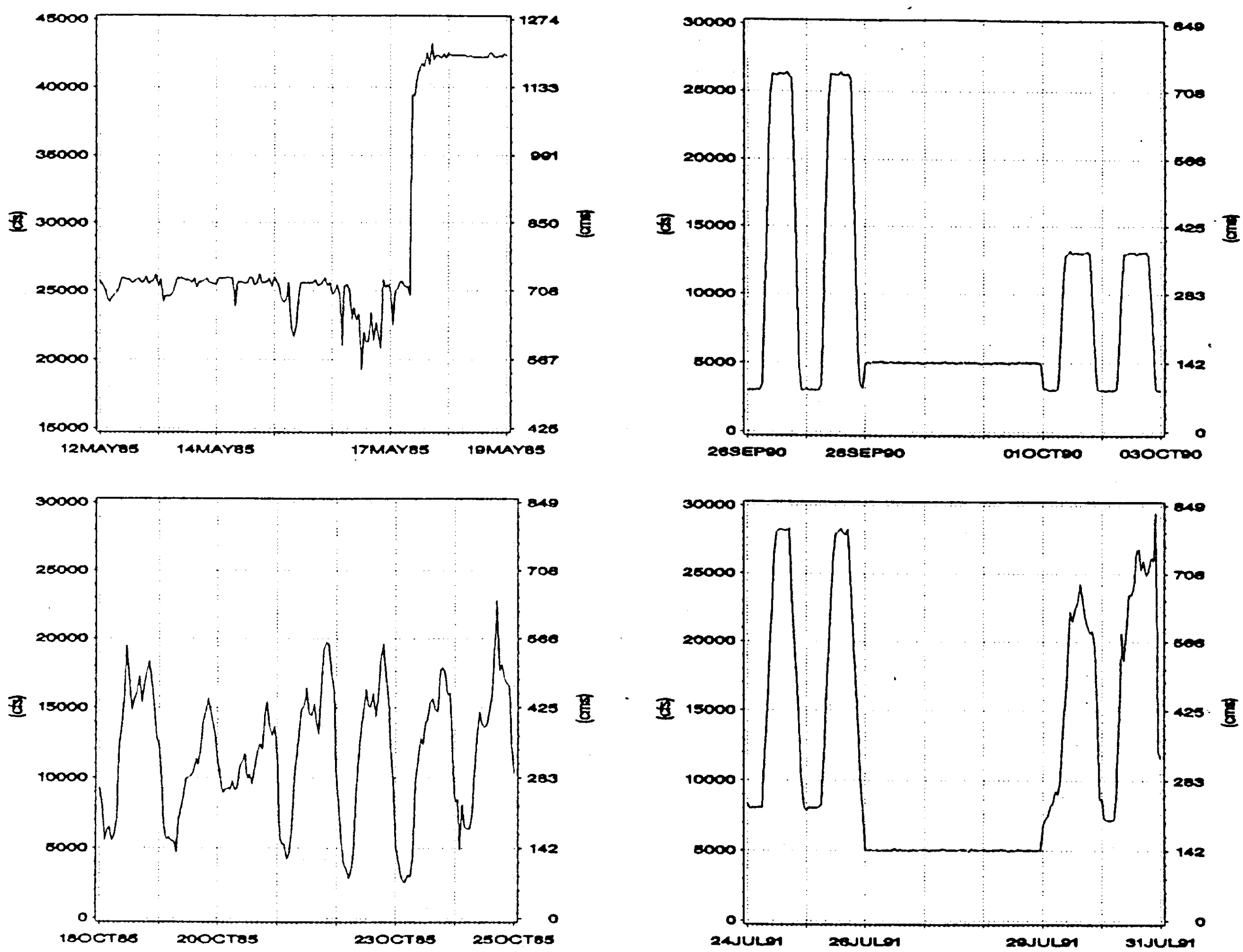


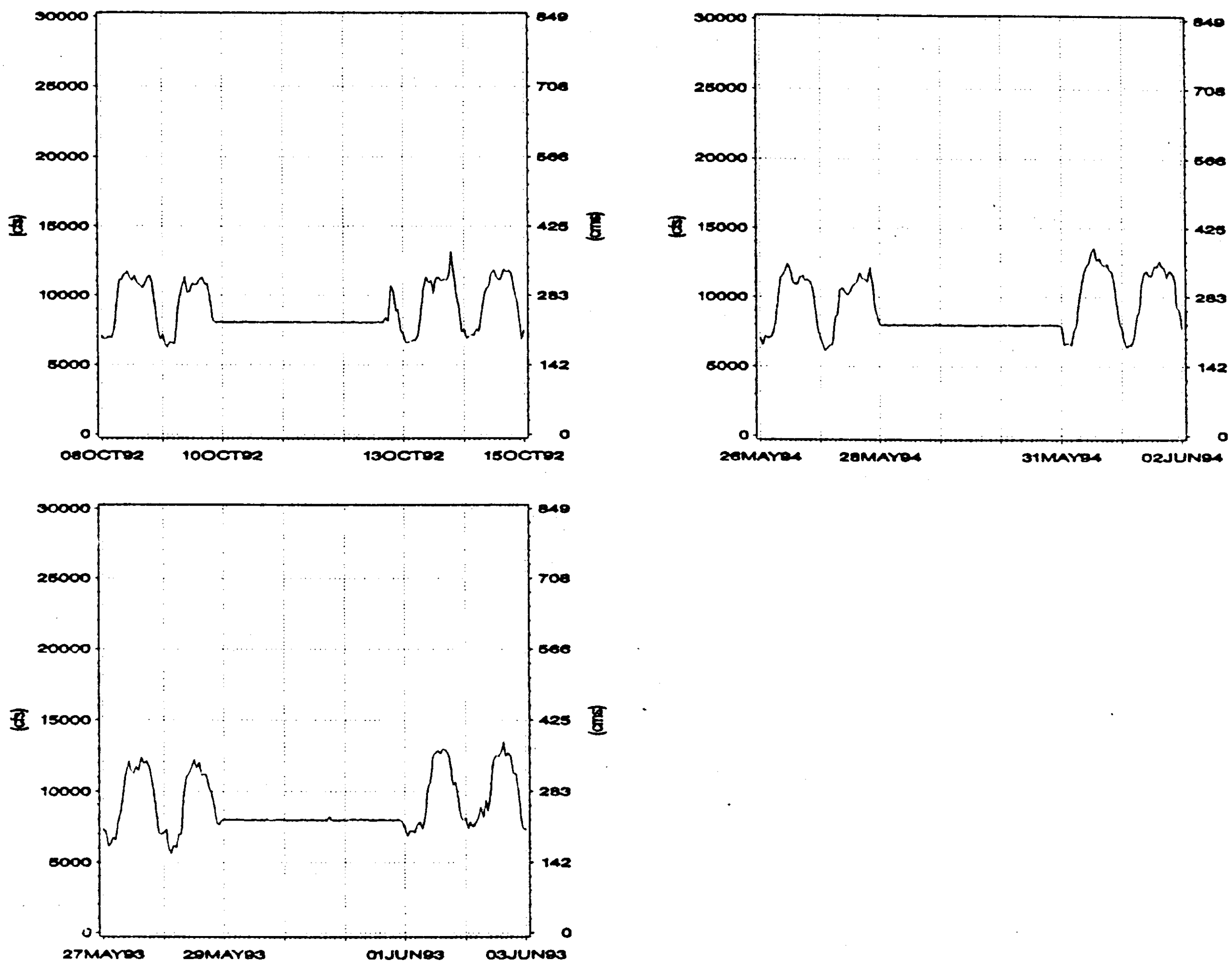
Appendix I. Hydrograph showing weekly minimum and maximum flows from Glen Canyon Dam for calendar years 1980 through 1994. (All hydrographs are provided by GCES, Bureau of Reclamation, Flagstaff, Arizona.)



Appendix II. Hydrographs showing hourly releases from Glen Canyon Dam for a 21 day period covering certain research flows described in this report.



Appendix III. Hydrographs showing hourly releases from Glen Canyon Dam for a seven day period centered on certain research flows described in this report.



Appendix III (continued). Hydrographs showing hourly releases from Glen Canyon Dam for a seven day period centered on certain research flows described in this report.