SPATIAL AND TEMPORAL TRENDS IN THE SIZE AND NUMBER OF BACKWATERS BETWEEN 1935 AND 2000, MARBLE AND GRAND CANYONS, ARIZONA

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1.0 ABSTRACT

The decline in native fish populations in the Colorado River in Marble and Grand Canyons over the past few decades has led biologists and river managers to investigate possible causes of that decline. One potential cause is declining habitat availability, including changes in the conditions of the backwater habitats used by nursery fish. Backwaters of the post-dam Colorado River in Grand Canyon occur in inundated return current channels in the lee of eddy bars. We evaluated spatial and temporal trends in backwater size and number based on: 1) analyses of detailed ground survey data from five eddy bars, and 2) interpretation of historical aerial photographs of five reaches totaling 21 km. From the survey data, we developed topographic maps of each eddy bar and evaluated the potential backwater area and volume at each survey site as a function of discharge. The results of this analysis indicated that the relationship between discharge and backwater condition changes from year to year at each site, and it also varies among sites in a given year. Variations in backwater volume were larger than variations in backwater area, demonstrating that volume is the more sensitive indicator of backwater condition because it accounts for differences in size between deep backwaters and shallow ones. Analyses of aerial photographs involved delineation of all backwaters in five study reaches between 1984 and 2000, and we delineated all backwaters between 1935 and 2000 within two study reaches. In all reaches, backwater size was greater in October 1984 than at any other time during the period of record; the number of backwaters was largest in 1984 and 1990. Time series of backwater conditions within each reach showed qualitatively that floods tended to increase backwater area and the absence of floods tends to decrease backwater area, while there was no apparent relationship between floods and backwater numbers. Although the area and number of backwaters in each reach showed large temporal variation, this variation appeared to be within the range of variability observed during the period of record. We found no evidence for a progressive increase or decrease in the availability of backwater habitats.

2.0 INTRODUCTION

The aquatic environments of the Colorado River in Marble and Grand Canyons have been physically and biologically altered by the construction and operation of Glen Canyon Dam (U.S. Department of the Interior 1995), and changes in habitat have occurred coincident with declining populations of native fish species. In particular, the proportion of native fish populations in nursery and subadult age classes has decreased (Minckley 1991). Prior to operation of the dam, spring peak flows facilitated the retention of water in the mouths of tributaries such as the Little Colorado River, which are assumed to have served as spawning and rearing areas for native fish from March to June each year (Valdez and Ryel 1995). Drifting larvae are assumed to have remained in the still water at tributary mouths, where warm water enabled rapid growth of nursery fish (Valdez and Ryel 1995). The post-dam absence of seasonal pools in tributary mouths potentially allows larval fish to be swept into the cold, clear water of the regulated Colorado River (Robinson et al. 1998). The hypolimnetic releases from the dam have decreased water temperature and increased water clarity, respectively, leading to decreased growth rates of native fish, decreased swimming ability (Ward et al. 2002), and increased vulnerability to visual predators (Clarkson and Childs 2000). Non-native fish were introduced both accidentally and for the purpose of sport fishing, and these exotic species may compete with native fish or prey upon their young (McAda and Kaeding 1989). In the post-dam riverine ecosystem, embayments of stagnant flow in the lee of reattachment bars provide habitat for juvenile humpback chub (Valdez and Ryel 1995, Hoffnagle et al. 1999). One objective of river management is to identify dam releases that form and maintain these backwater habitats. Biologists have suggested that reductions in native fish habitats, such as backwaters, have contributed to declining fish populations in the Colorado River, particularly in the reach immediately downstream from the Little Colorado River (Converse et al. 1998, Robinson et al. 1998), which is known to be a spawning area for native fish (Valdez and Ryel 1995).

The evidence concerning the linkage between backwater availability and discharge is limited spatially and temporally. The 1996 controlled flood both widened and deepened the return current channel at one site near the mouth of the Little Colorado River (Andrews et al. 1999) and increased the habitat complexity of that site. Although the backwaters increased in number as a result of the 1996 controlled flood and were occupied by both native and exotic fish (Hoffnagle et al. 1999), new backwaters quickly filled with sediment and therefore were not usable by fish on an ecologically meaningful time-scale (Brouder et al. 1999). Although the September 2000 spike flow increased the total area of backwater habitats at a reach-wide scale immediately after the flow (Schmidt et al. 2003), the longevity of these habitats is unknown.

One objective of this study was to describe how the area and volume of backwaters changes in relation to discharge at five eddy bars and how this relationship changes from year to year. The second objective was to describe how the number and size of backwaters in five reaches, totaling 21 river km, has changed during the period 1984-2000. For reaches of the Colorado River near the mouth of the Little Colorado River, which is ecologically important for native species such as the humpback chub (Robinson et al. 1998, Valdez and Ryel 1995), we have additional data for the interval 1935-1984. Thus, this study allows assessment of the spatial and temporal variability of backwater area and number over timescales of decades and spatial scales of tens of kilometers. These larger temporal and spatial scales provide river ecologists with useful data that can be compared with life history data for species that utilize these habitats. This report is submitted in partial fulfillment of cooperative agreement 01WRAG0059 and modifications between Utah State University and the Grand Canyon Monitoring and Research Center.

3.0 GEOMORPHOLOGY OF BACKWATERS

Backwaters exist at all discharges in those sites where flow is stagnant or of very low velocity. Although embayments of stagnant flow may exist in the lee of any large obstructions, the dominant location of backwaters within the constrained hydrology of the post-dam Colorado River is in inundated, but inactive, primary eddy return current channels (Fig. 1). Inactive eddy return current channels are surrounded on three sides by sand deposits and therefore contain water that is either completely still or moving at a very low velocity. Native fish larvae can actively swim within, and sometimes among, these stagnant backwater habitats (Robinson et al. 1998), which are thought to provide beneficial habitat conditions for young fish due to their low current velocities, warmer water temperatures, and potentially large concentrations of plankton and macroinvertebrate food sources (Valdez and Ryel 1995, Childs et al. 1998, Hoffnagle et al. 1999).

Although river managers seek to understand the direct linkage between dam releases and backwater size and abundance, this linkage is not straightforward. High flows increase relief of the bed topography, increase the elevation of bar crests, and deepen the return current channel (Wiele et al. 1999). Such a trend generally increases backwater volume, and deeper return current channels result in backwaters that persist over longer periods of time. Therefore, we might expect to see increases in backwater size and number following large floods. However, there is great spatial variation in resultant bar forms following any specific prescriptive flow event, such as the 1996 controlled flood (Schmidt et al. 1999). This spatial variation may confound interpretation of the impacts of any prescriptive flows if the only data are derived from a few measurement sites.

4.0 METHODS

We described backwater availability using two data sets. The first data set is that surveyed by the Sandbar Studies Group of the Dept. of Geology at Northern Arizona University (NAU) as part of an ongoing contract with the Grand Canyon Monitoring and Research Center. These topographic data provide precise descriptions of bar and bed topography for 20 sites on various dates since 1990 (Beus and Avery 1992). The second data set is that derived from analyses of aerial photographs acquired between 1935 and 2000 in five reaches totaling 21 km (Schmidt and Leschin 1995, Schmidt et al. 1999, Sondossi 2001, and Sondossi et al. 2002, Schmidt et al. 2003). In both data sets, we defined potential backwaters as the area of an embayment enclosed on three sides by land and whose streamward boundary is a line 45 degrees from the tip of the bar to the adjacent shore (Fig. 1).

The Colorado River hydrograph showed tremendous variation during our period of record due to both natural floods and flow management (Fig. 2), and backwater conditions must be interpreted in the context of the hydrograph. Dam operations beginning in 1963 included smaller peak flows, higher base flows, and larger daily fluctuations in discharge than in the pre-dam era. The period between 1963 and 1983 contained only one large dam release of approximately 1,290 m^3/s in 1980, and thus could be characterized as a period of no floods. Between 1983 and 1986, there were releases greater than 1,300 m^3/s at least once per year, including the 1983 release of 2,755 m^3/s, so frequent flooding was characteristic of this period. No releases beyond power plant capacity (about 875 m^3/s) occurred between 1987 and 1996. After 1991, dam releases were consistently below 708 m^3/s, and only the releases of March 1996 (1,300 m^3/s), November 1997 (767 m^3/s), and June and September 2000 (787 m^3/s) were large enough to completely inundate the reattachment bars that form the backwaters studied here. Although sediment flux data would enhance the contextual interpretation of backwater trends, continuous sediment data are not available prior to 1999 (D. Topping, personal communication).

4.1 Site-specific changes in backwater area: models based on survey data

The first data set was used to precisely define the area and volume of backwaters, and to evaluate the variability of backwater availability at different times, or discharges, and from site to site. The detailed NAU topographic surveys, which are accurate within 5 cm, facilitated the development of fine-scale topographic maps that were used to determine potential backwater areas at discharges other than those at the time of survey. We recognize that bar topography changes dynamically with flow, and our methods allow an assessment of how the relationships between backwater availability and flow change with time and from place to place.

The NAU surveys were used to develop three-dimensional models of the topography of specific eddy bars, and identify the potential area of backwaters at various river stages. We used NAU survey data at five sites (Fig. 3) to develop triangular interpolated networks (TINs), or three-dimensional topographic models, of eddy-bar topography for multiple survey dates (Table 1). Each TIN was converted to a line coverage containing 0.5-m contours. We used each contour to determine the existence and dimensions of embayments, and we delineated the streamward side of all backwaters (Fig. 4). The areas of the polygons delineated for each contour, and the volumes corresponding to the surveyed topography within each backwater polygon, were quantified in a geographic information system (GIS). Based on the stage-discharge relationships provided by NAU (Table 2; see Kaplinski et al. 1995 for methods), we identified the discharge required to attain each stage of our 0.5-m contours. Therefore, we created a dataset consisting of the potential backwater area and volume at 0.5-m intervals, and the river discharge corresponding to these stages, for multiple points in time at each of our five sites.

4.2 Reach-wide changes in backwater area between 1984 and 2000: aerial photographic analysis

We delineated backwater areas in five study reaches (Fig. 3) previously mapped by Schmidt and Leschin (1995), Schmidt et al. (1999), Sondossi (2001), Sondossi et al. (2002), and Schmidt et al. (2003). The locations and characteristics of these five reaches are described in Table 3. Schmidt et al. (2002) documented widespread changes in the style of sand storage in these study reaches and decreased sand area in some reaches. Two reaches, the Upper and Lower Little Colorado River (LCR) reaches, lie adjacent to the confluence of the Little Colorado River, which is an important habitat for native fish (Converse et al. 1998, Robinson et al. 1998).

Backwaters were delineated on several series of aerial photographs that were acquired between 1935 and 2000 (Table 4). For all series of maps except August and September 2000, backwaters were identified on aerial photographs and added to our GIS database using a combination of transparent overlays on aerial photographs and on-screen viewing of previously completed mapping and digital orthophotographs. Backwater areas in August and September 2000 were delineated digitally on georeferenced photographs. This multi-temporal delineation of backwaters produced a GIS containing a census of all backwaters present in each of the five study reaches at the time of photography. Although some studies (Sondossi 2001, Schmidt et al. 2002) have utilized correction factors to adjust for difference flow discharges at the time of photography, these correction factors require the assumption of a fixed relationship between discharge and backwater area. Due to the observed spatial and temporal variability in the relationship between backwater area and discharge from our analysis of NAU data, we were unable to apply such correction factors to backwater areas.

The time series produced by mapping backwaters on multi-temporal aerial photographs included the total backwater area and the total number with backwaters in each reach. The number of backwaters was defined as the number of persistent eddy bars (sensu Schmidt and Leschin 1995) that contained backwaters, standardized by reach length. Due to constraining features such as rockfalls and debris fans, individual eddy bars in the Grand Canyon do not migrate, and their size and configuration can be monitored over time (Schmidt and Leschin 1995, Schmidt et al. 2002). Persistent eddy boundaries represent the aggregate area occupied by eddy bar deposits during the entire period of record. Persistent eddy bars provide a useful point of reference for monitoring backwaters because eddy bars include the secondary channels that form backwater habitats. The persistent eddy boundaries used in this study were developed for the period between 1935 and 2000.

We hypothesized that the area and number of backwaters would be greatest following flood events and smallest following long periods without floods. Floods tend to increase the topographic variability of eddy bars, which leads to deep return channels (Wiele et al. 1999), and the absence of floods leads to backwaters becoming shallower and smaller. Although site-specific responses to floods may be highly variable (Schmidt et al. 1999), we expected reach-scale metrics of backwater condition to reflect an average system response to high flows.

Using a two-way analysis of variance, we assessed the statistical significance of spatial differences in backwater condition among our five reaches, and of temporal differences in backwater condition for all reaches. Thus, we tested the effects of reach designation and time on backwater area, and repeated the analysis to test for effects on backwater number. Thus, we tested for significant differences in backwater condition among reaches, and for the aggregate of all reaches over time.

We identified important reach-scale changes in backwater area relative to the error of our methods. Planimetric and attributing errors, as well as human error, may influence the overall accuracy of spatial data (Congalton and Green 1998). An error analysis of the mapping and transformation methods of previous studies (Schmidt and Leschin 1995, Schmidt et al. 1999, Sondossi 2001, Sondossi et al. 2002) was described by Schmidt et al. (2002), who compared their delineation of fluctuating-flow deposits, based on aerial photographs, with the extent of these deposits surveyed by NAU at 13 eddy bars in Marble and Upper Grand Canyons. This error analysis yielded an overall accuracy of 84.8% and an overall error of 15.2%, which encompasses the bias and precision of their methods (Schmidt et al. 2002). Since the basic methods of mapping and spatial transformation used here are the same as those used by Schmidt et al. (2002), we assume the error is the same. In this report, each figure showing backwater area includes an error bar that represents ±15.2% of the reported area. Tests of statistical significance were not possible because the time series for each reach included only one datum for each point in time.

5.0 RESULTS

5.1 Site-specific changes in backwater area: models based on survey data

Analyses of three-dimensional models for five sites, based on NAU survey data, show that the relationship between discharge and backwater area and volume varies among sites, and among different sample dates at the same site (Figures 5 and 6). The discharge corresponding to the maximum potential backwater area and maximum potential backwater volume on a particular date, represented by the mode of each relation, varies spatially and temporally. Only two sites, those at river-mile 30 and river-mile 65, provided any evidence that backwater area and volume increase following floods. Although the precise shape and steepness of the curves of backwater area and volume were not exactly the same, these two indicators of backwater status show similar spatial and temporal trends. The mean backwater area and volume (Figs. 5 and 6) is typically greatest at discharges less than 340 m^3/s at the Above Cathedral, Eminence Break, and Carbon Canyon sites. The mean backwater volume at the Fence Fault Canyon site is greatest around 566 m^3/s. The Crash Canyon site contained backwaters only in 1993, and the greatest backwater size in that year occurred at about 773 m^3/s.

The curves describing backwater area as a function of discharge changed considerably among survey dates at each site. The shapes of the curves were unimodal at some sites and at some dates, while they were bimodal in other cases. At some sites, in some years, the area of backwaters at 142 m^3/s was greater than that at 227 m^3/s, while on other dates or at other sites, the area was greater at 227 m^3/s. There were no trends regarding which sites or years contained larger backwaters at 142 or 227 m^3/s; in fact, the relationship between discharge and backwater area changed at each site from year to year, and differed among sites in each year. This high degree of spatial and temporal variability, even at these small and regularly occurring flows, indicates the dynamic nature of backwater habitats for native fish at different times and from site to site.

The relationships between discharge and backwater volume also varied from site to site, and from year to year at the same site (Figure 6). Spatial and temporal changes in backwater volume tended to be proportionally larger than trends in backwater area. For example, the modes of the lines in Figures 5 and 6 for the Carbon (65-mile) site show that the maximum potential backwater area increased at this site by a factor of 1.5, while the maximum potential backwater volume increased by a factor of about 2.5, following the September 2000 spike flow of 878 m^3/s. Similarly, between April 1996 and August 2000, the maximum potential backwater area decreased at the Fence site by less than 25% and the maximum potential volume decreased by more than 50%. These data indicate that volume is more sensitive than area as an indicator of overall backwater size.

5.2 Reach-wide changes in backwater area: aerial photographic analysis

Interpretation of long-term changes in reach-average backwater availability is difficult because of the significant temporal and site-to-site variation described above. However, reach-scale time series in backwater area and number provide an average metric of backwater condition, and they incorporate sites that increase and those that decrease during a given time interval. The time series presented here include both the total number of persistent eddies with backwaters and the total backwater area in each reach; trends are described at both system-wide and reach scales.

At the system-wide scale, analyses of variance indicated that the Upper LCR reach contains a relatively large number of small backwaters, and the Lower LCR reach contains many large backwaters. Backwater conditions in the Upper and Lower LCR reaches were statistically different than in all other reaches. Backwater area in the Lower LCR reach was significantly greater than in other reaches, while backwater areas in the Redwall Gorge and Upper LCR reaches were significantly lower than in other reaches ($p<0.001$). The Upper and Lower LCR reaches contained significantly more backwaters than the other three reaches ($p<0.001$). While there was no significant temporal change in backwater area at a system-wide scale over the entire period of record ($p=0.412$), the number of backwaters was significantly greater in 1984 and 1990 than in other years ($p=0.003$).

When each of the five reaches was considered separately, the time series of backwater area provided qualitative evidence that backwater area was generally greatest after floods and smallest after periods of no floods (Fig. 7a). Changes in backwater areas between 1984 and 1996 provide an indication of the effects of the absence of floods on backwater availability. Nearly all reaches showed relatively large backwater areas in

1984 that subsequently decreased until 1996; the only exceptions to this trend are the LCR reaches, which experienced increases in backwater area following the 1993 flood in the Little Colorado River. Backwater area increased in the Redwall, Upper LCR, and Lower LCR reaches following the 1996 controlled flood; it also increased in the Point Hansbrough, Upper LCR, and Lower LCR reaches following the September 2000 spike. The latter increases in backwater area coincided with a decrease in the area of sand between stages corresponding to 227 and 878 m^3/s (Schmidt et al. 2003), suggesting that the area of backwaters and the area of sand between these stages are inversely related.

Despite the above qualitative evidence linking floods and backwater area, there is little evidence that floods increase the number of backwaters and the absence of floods leads to decreased numbers of backwaters. Throughout the period of record, all reaches contained more backwaters in 1984 than in any other year (Fig. 7b). In the absence of floods between 1984 and 1996, the number of backwaters decreased only in the Redwall and Upper LCR reaches. The effects of the 1996 controlled flood varied widely among reaches, with some reaches gaining backwaters, some reaches losing backwaters, and others experiencing no change in the number of backwaters. The September 2000 spike flow increased the number of backwaters in the Redwall, Upper LCR, and Lower LCR reaches, and did not change the number of backwaters in the Lees Ferry and Point Hansbrough reaches.

There is no evidence of a progressive trend in backwater availability, based on the time series of backwater area and number between 1935 and 2000. Within the two reaches studied prior to 1984, the Upper and Lower LCR reaches, we know that the number and area of backwaters in 1984 were as great as at any other time. All reaches showed decreases in backwater area between 1984 and March 1996, and most reaches contained fewer backwaters in March 1996 than in 1984. However, the post-dam variability of the number and area of backwaters falls within the range of variability observed during the period of record and does not indicate a long-term decline in backwater condition.

6.0 CONCLUSIONS

The high spatial variability of the relationship between discharge and backwater area indicates that flows do not uniformly affect all backwaters. System-wide metrics of backwater conditions have not changed significantly over time, yet reach-scale trends qualitatively indicate that average backwater area increased following large floods and decreased in the absence of such floods. River discharge is thought to affect the number and area of backwaters, yet the variable responses of individual eddy bars to floods and base flows lead to large year-to-year changes in backwater size. These year-to-year changes may be larger than changes in backwater size that occur over multiple years or even decades. Because fluctuations in backwater area and number were distributed throughout our period of record and are within the observed range of variability, there is little evidence of a progressive change in backwater condition throughout the period of record.

Both the area and number of backwaters are important reach-scale indicators of habitat condition with respect to juvenile fish. For example, the small size of backwaters in the Upper LCR reach may allow faster warming of these habitats; thus, this reach may provide better nursery habitat than reaches with only a few large backwaters. At site-specific scales, backwater volume appeared to be a more sensitive indicator than area of backwater size. However, interpretation of changes in backwater volume in the context of fish habitat may be problematic due to the relationship between backwater depth and water temperature. For example, large-volume backwaters may be deep and therefore contain colder water than smaller, shallower backwaters, which warm more quickly. Due to the negative effects of low water temperature on native fish (Clarkson and Childs 2000, Ward et al. 2002), large-volume backwaters do not necessarily provide optimal habitat for these fish. Thus, backwater area may be a better indicator of habitat utility for native fish. Biological data regarding backwater utilization by native fish may illuminate the importance of area, volume, or area:volume ratios as indicators of backwater condition relative to optimal habitat conditions.

The appropriate scale for future backwater monitoring must account for the high spatial and temporal variability of backwater area and number. The spatial distribution of backwaters was significantly different among reaches, and the ecologically important Upper and Lower LCR reaches contained more backwaters than the other three reaches. Therefore, trends observed in other reaches may not reflect backwater conditions around the Little Colorado River. The five reaches studied here were of sufficient length to provide reach-scale and system-wide trends in backwater condition that are interpretable and potentially ecologically meaningful. The temporal variability of individual backwaters may unduly influence reach-scale indicators of backwater status. At small temporal scales, fluctuations such as those observed in the Upper and Lower LCR reaches may appear to be part of a long-term trend, while in reality they represent a wide range of variability within a long-term trend of no change. The period of record studied in the Upper and Lower LCR reaches included pre-dam observations and captured the wide range of variability in backwater condition during the period of record, and we recommend that monitoring programs for reaches not studied here should include baseline data from the pre-dam era. In summary, any backwater monitoring regime must include reaches long enough to capture variable site-specific responses to flow management, and enough temporal observations to determine whether observed changes are real trends or simply indications of high system variability.

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8.0 TABLES AND FIGURES

Table 1. The dates and locations of the NAU surveys used in the topographic analysis.

Dates	Above Cathedral (Mile 3L)	Fence Fault Canyon (Mile 30R)	Eminence Break (Mile 45L)	Crash Canyon (Mile 62R)	Carbon Canyon (Mile 65R)
Sept. 1990	x	x	x		
Oct. 1992			x		
Apr. 1993				x	
Feb. 1996	x	x	x	x	x
Apr. 1996	x	x	x		x
Sept. 1996	x	x	x	x	x
Aug. 2000	x	x	x	x	x
Sept. 2000	x	x	x	x	x

Table 2. Stage-discharge relationships, developed by NAU (provided by Joe Hazel), for each site. Q represents discharge, in cubic feet per second, and z represents the river stage, in meters. These relationships were used to calculate the discharge corresponding to each 0.5-m contour.

Site	Stage-discharge relationship
Mile 3L	$z = 942.0007 + (Q*0.000175575) + (Q^2*(-1.48399*10^{-9}))$
Mile 30R	$z = 875.2755 + (Q*0.000241504) + (Q^2*(-1.90257*10^{-09}))$
Mile 45L	$z = 857.4392 + (Q*0.000175441) + (Q^2*(-1.1119*10^{-9}))$
Mile 62R	$z = 822.076 + (Q*0.000143841) + (Q^2*(-6.74106x10^{-10}))$
Mile 65R	$z = 817.222 + (Q*0.000152596) + (Q^2*(-1.10993x10^{-09}))$

Table 3. Characteristics of the five study reaches.

Reach	Lees Ferry	Redwall Gorge	Pt. Hansbrough	Upper LCR	Lower LCR
Reach length (miles)	2.1	2.9	3.1	1.8	3.5
River miles	0.8 – 2.9	29.3 – 32.2	42.4 – 45.5	60.0 – 61.8	61.8 – 65.3
Number of persistent eddies	11	20	26	17	37

Table 4. Descriptions of the photographic series used in reach-scale mapping of backwaters. Study reaches are abbreviated as follows: LF = Lees Ferry, RW = Redwall Gorge, PH = Point Hansbrough, ULCR = Upper Little Colorado River, and LLCR = Lower Little Colorado River.

Date	**Scale**	**Film type**	**Reach**	**Discharge (m^3/s)**
Mid-1930's	1:30,000-35,000	Black and white	ULCR, LLCR	85-170
May 1965	1:12,000	Black and white	ULCR, LLCR	708-764
June 1973	1:14,400	Black and white	ULCR, LLCR	297-411
Oct. 1984	1:3000	Black and white	RW, PH, ULCR, LLCR	142
June 1990	1:4800	Color infrared	ULCR, LLCR	142
Oct. 1992	1:4800	Color	PH, ULCR, LCCR	227
May 1993	1:4800	Color	ULCR, LLCR	227
March 1996	1:4800	Black and white	RW, ULCR, LLCR	227
April 1996	1:4800	Black and white	LF	290
			RW	314
			PH, ULCR, LLCR	385
Sept. 1996	1:4800	Black and white	LF	227
			RW	235
Aug. 2000	0.6-m pixel resolution	Black and white	LF, RW, PH, ULCR, LLCR	225
Sept. 2000	0.6-m pixel resolution	Black and white	LF, RW, PH, ULCR, LLCR	225

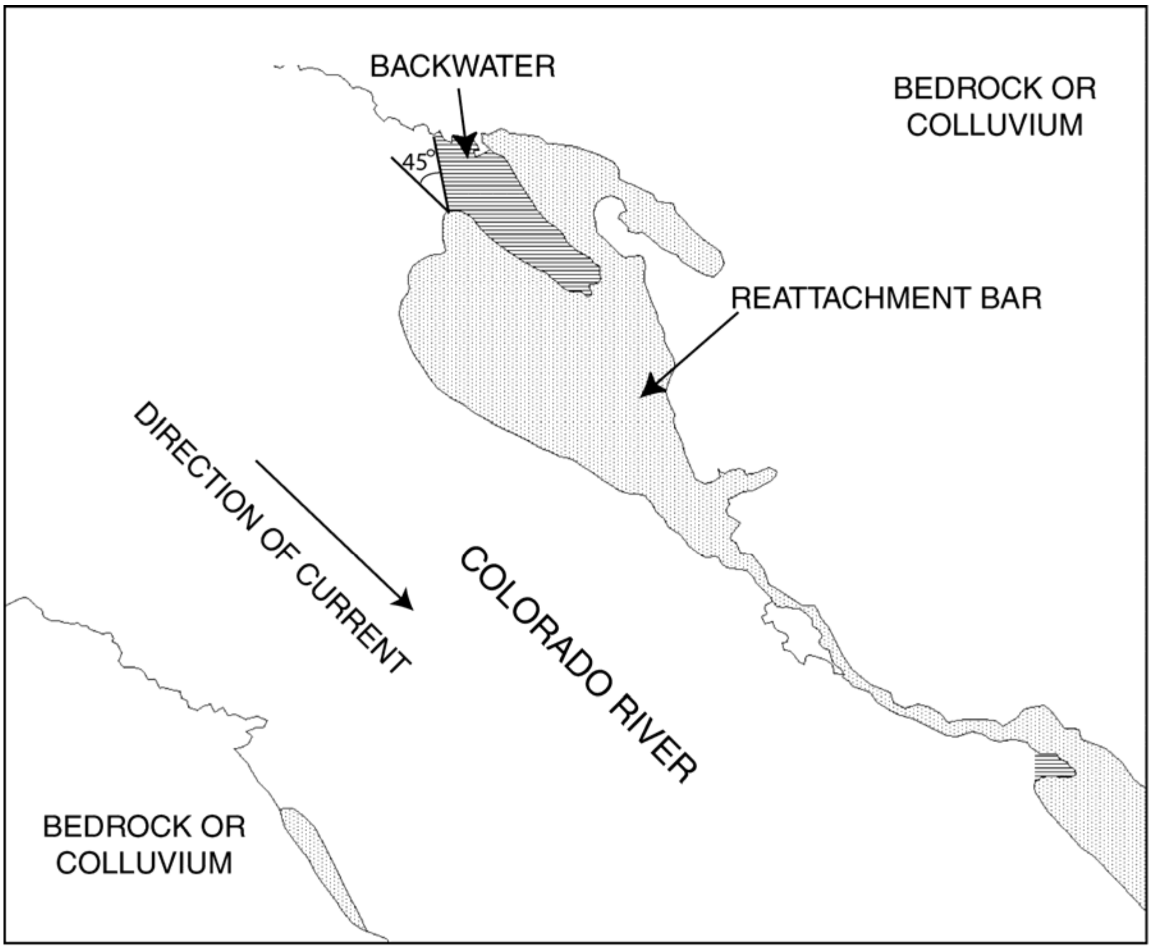

Figure 1. Map showing a sample backwater opening in the upstream direction. The upstream boundary of the backwater was drawn at 45 degrees with respect to the main current direction.

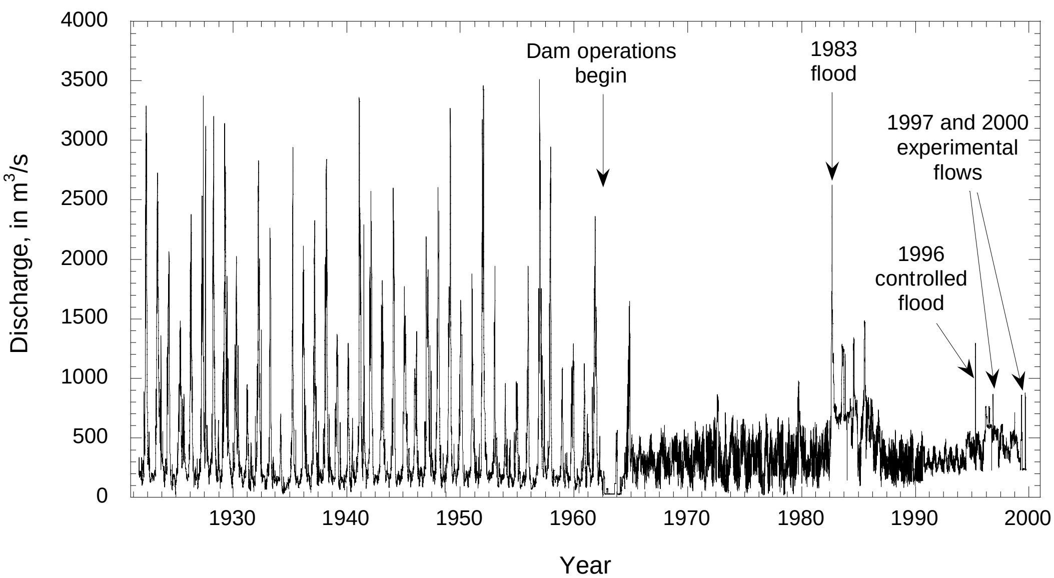

Figure 2. Instantaneous discharge of the Colorado River at Lees Ferry between 1921 and 2000.

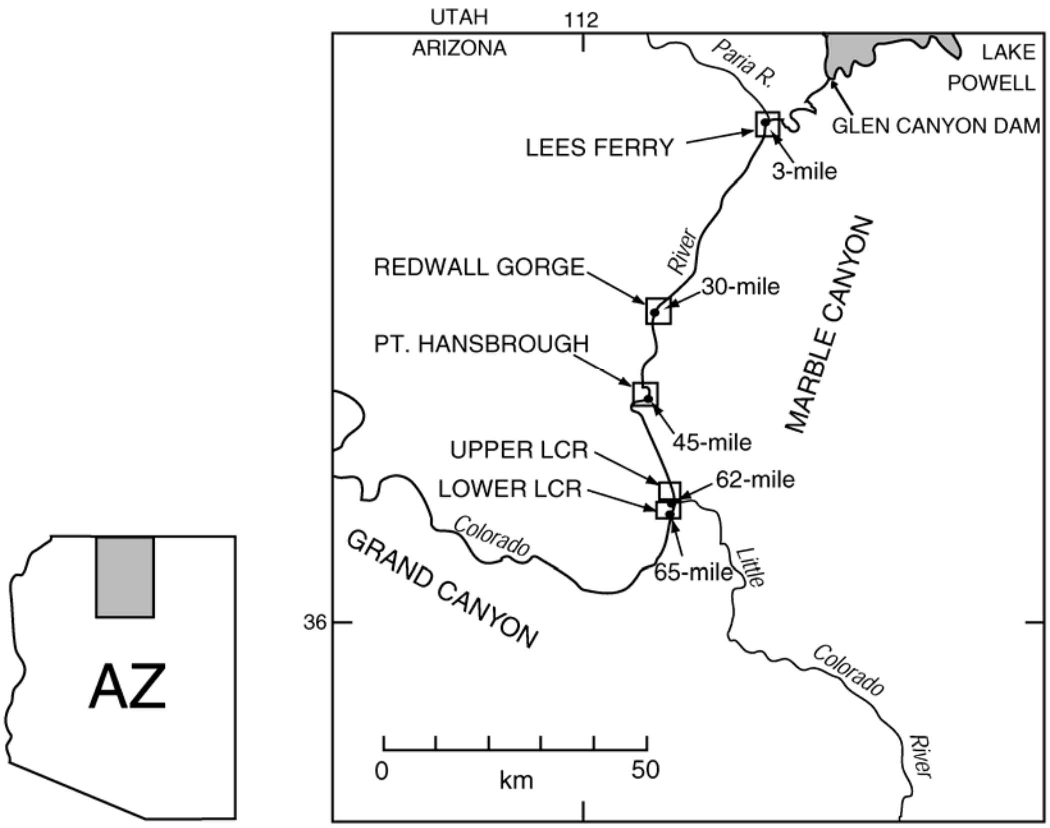

Figure 3. Map showing the five study reaches where photogeologic mapping of backwaters was conducted (delineated here with black outlines) and the five sites where backwaters were delineated based on NAU survey data (arrows and river-mile locations).

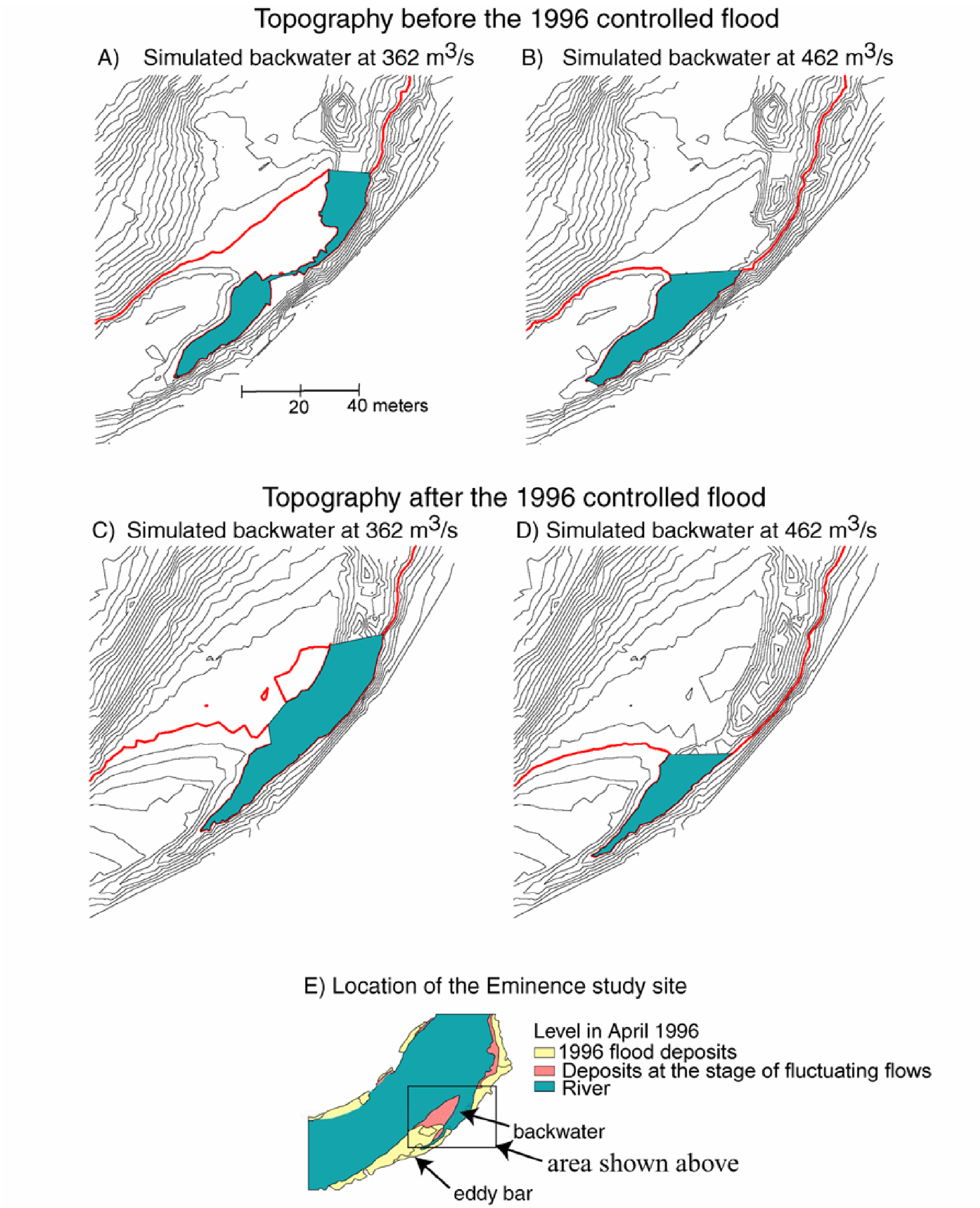

Figure 4. Map showing a sample topographic map developed from NAU survey data at the Eminence Break (45-mile) site in February 1996 (A and B) and April 1996 (C and D), with a larger perspective of the eddy bar as mapped in April 1996 (E). Gray lines represent 0.5-m contours, and red contours represent elevations of 859.5 m (A and C) and 860.0 m (B and D). These stages correspond to discharges of 362 and 462 m^3/s, respectively. The shaded polygon delineates the simulated backwater at the specified stage.

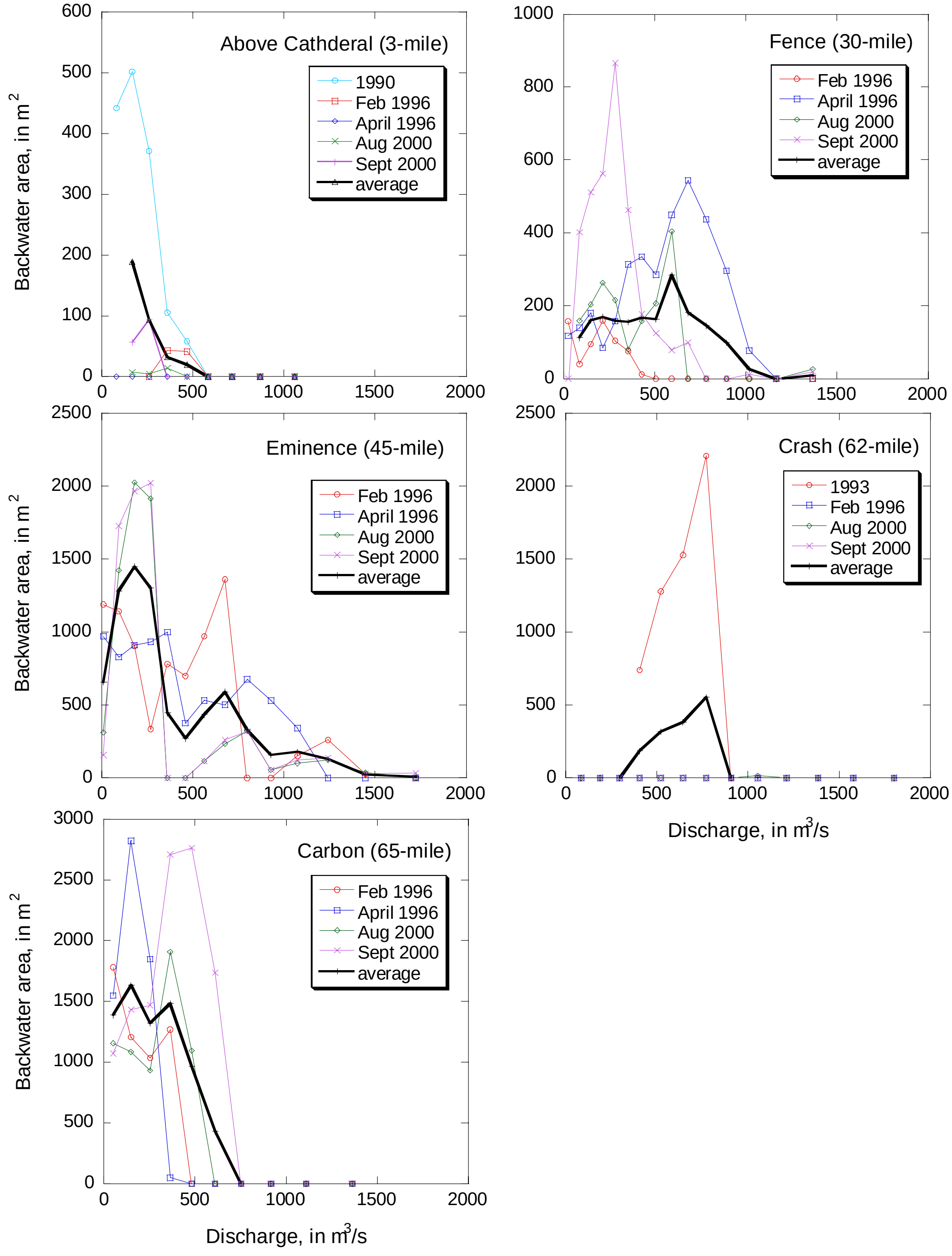

Figure 5. Relationships between river discharge and potential backwater area at five sites surveyed by NAU. Colored lines represent specific survey dates. Thick black lines represent the mean backwater area at a given discharge. Not the different scales for y axes among sites.

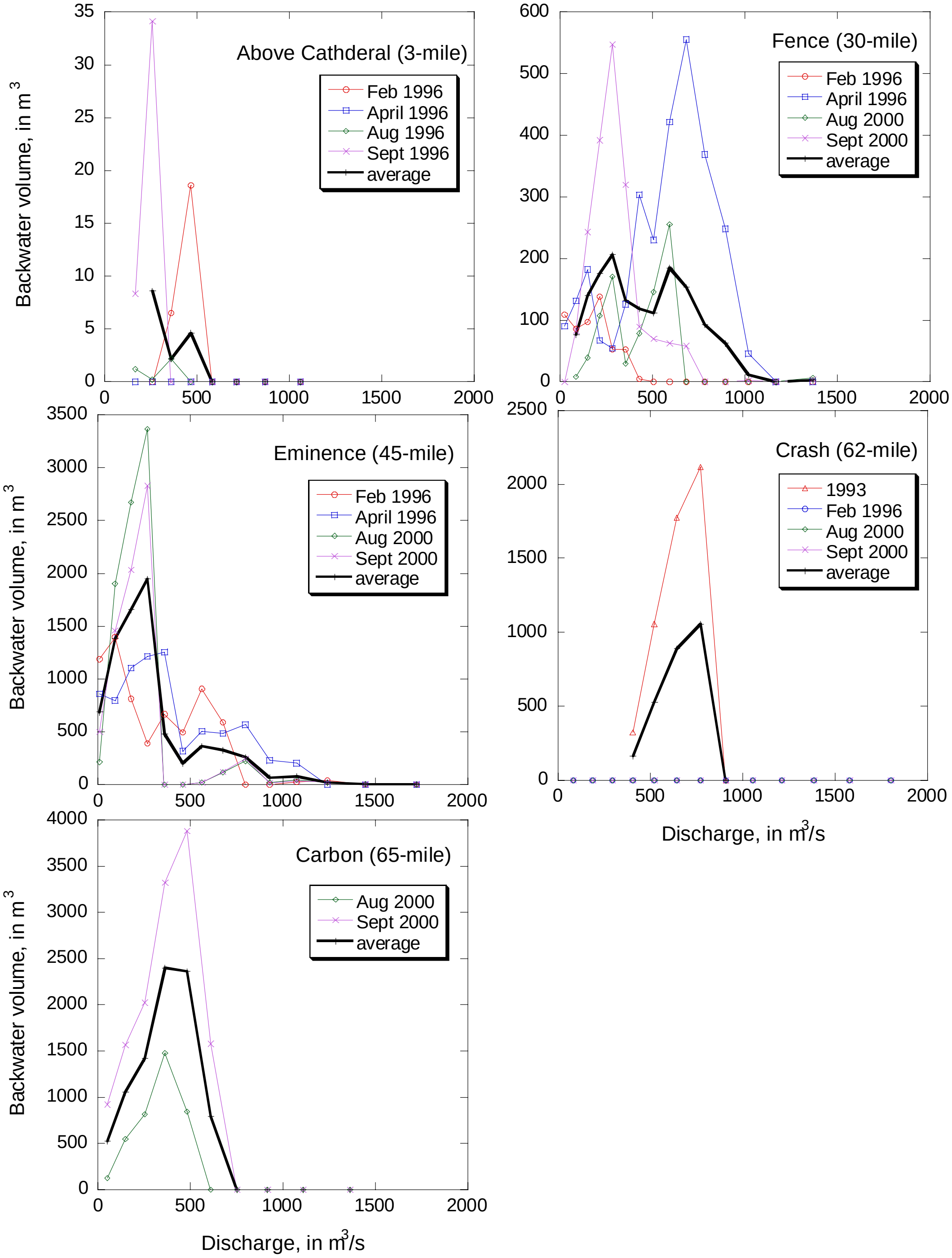

Figure 6. Relationships between river discharge and potential backwater volume at five sites surveyed by NAU. Colored lines represent specific survey dates. Thick black lines represent the mean backwater volume at a given discharge. Note the different scales for y axes among sites.

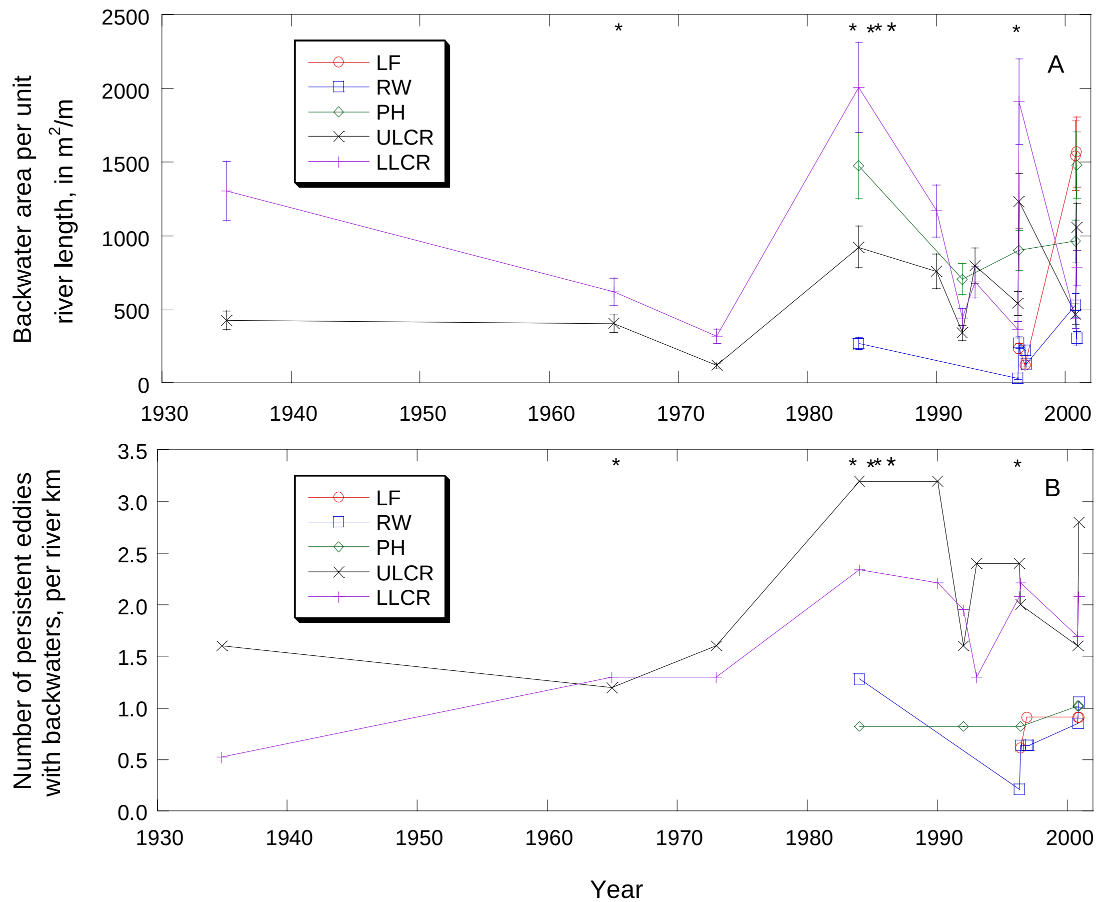

Figure 7. Time series of backwater area (A) and the number of persistent eddies with backwaters (B) per unit river length. Time series of backwater area (A) includes error bars representing an overall error rate of +/-15.2%. Study reaches are abbreviated as follows: LF = Lees Ferry, RW = Redwall Gorge, PH = Point Hansbrough, ULCR = Upper Little Colorado River reach, and LLCR = Lower Little Colorado River reach. Asterisks (*) indicate years in the post-dam era with peak discharges >1275 m^3/s.