SPATIO-TEMPORAL CHANGES IN COLORADO RIVER BACKWATERS DOWNSTREAM FROM GLEN CANYON DAM, ARIZONA, 1965 - 1997

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EXECUTIVE SUMMARY

Habitat modification has been identified as a primary factor reducing recruitment success of native, warm-water fish species in the Colorado River downstream from Glen Canyon Dam. Reduced sediment transport and cold-stenothermic releases from Glen Canyon Dam, as well as introduction of numerous non-native fish species and fish diseases, have been held responsible for the 1978 Jeopary Opinion on the operations of Glen Canyon Dam. The recruitment niche for many young native fish includes safe nursery sites, with low velocity and warm (generally >16°C) water temperature. These refugial conditions exist downstream from Glen Canyon Dam in some Colorado River backwaters, which provide low-velocity, near-shore habitats that may warm substantially above the cold stenothermic temperature of the mainstream. The spatial habitat scale most relevant to a young fish is that of an individual backwater, and if that backwater is flushed by high, cold mainstream flows the young fish may not be able to tolerate the increased velocity and decreased temperature of the mainstream. Short-term (hourly, daily, weekly and seasonal) fluctuating flow releases from Glen Canyon Dam reduce habitat availability by dewatering or flushing these backwater habitats, and longer-term (yearly and longer) impacts of flood control result in terrestrialization of backwater habitats. These effects of Glen Canyon Dam have been implicated in the loss of native fish diversity in the Colorado River.

Grand Canyon backwaters form in return current channels (RCCs) associated with reattachment bars, as well as in ephemeral, near-shore habitats and in cobble bar pools. Colorado River RCCs and other backwaters undergo terrestrialization, through aggradation of tributary-derived sediments and development of marsh and woody vegetation. Therefore, the area and volume of individual backwaters as habitat for young native fish may change over time in this regulated river ecosystem. The Arizona Game and Fish Department (1996, including McGuinn-Robbins 1997 unpublished) has reported a long-term decline in reach-based backwater habitat availability from 1984 to 1995; however, changes in backwater habitat availability have not been examined at the scale of individual backwaters, which is the relevant spatial scale for young fish. Although the Glen Canyon Dam Environmental Impact Statement (1995) is largely focused on managing the river for native fish and their habitats, until the present there has been no system-wide assessment of whether and how individual backwaters have changed in area and volume over time and stage at the spatial scale that is most relevant to young native fish.

We are using aerial photography and videography collected from the river corridor from 1965 to 1997 to determine: (1) whether the area of individual Colorado River backwaters $\geq 100 m^2$ in area and detectable from aerial photography or videography has changed over time, from 1965 to 1997, and whether reach-based and system-wide patterns of change exist; (2) how the area of individual Colorado River backwaters $\geq 100\ m^2$ in area changed across the stage-discharge relationship in the early 1990's and the late 1990's, and whether these two time periods display comparable patterns in relation at individual, reach-based and system-wide spatial scales; and (3) whether backwater hypsometry (volume as a function of stage elevation) of selected large, characteristic Colorado River backwaters has changed from 1990 to 1997 in relation to tributary and mainstream sediment transport.

These analyses are using existing photographic imagery and the limited existing data. This project is providing an assessment of temporal and stage-related change in backwater habitat availability in relation to Glen Canyon Dam operations, including fluctuating mainstream flows (1990 to 1991), low daily flow fluctuations (1991 through 1995), through the 1996 Test Flow and high constant flows (1996 to 1997), as well as in relation to tributary sediment contributions. These analyses are being conducted in FY 1998 and FY 1999, and we expect to have the analyses completed by 31 March 1999 at a cost of $46,146.00 for Map Image Processing Software mapping, hypsometric analyses, and report and publication page costs.

This annual report updates the Grand Canyon Monitoring and Research Center on our progress to date. We have analyzed all relevant videography from 1990 through 1997 (20 runs) from Glen Canyon Dam to Diamond Creek, including a range of flows from 5,000 cfs to 45,000 cfs. We have compiled data on each backwater detectable in this videography, measuring the map area, greatest width, mouth width, length and shoreline perimeter. We are conducting replication error estimates on these measurements. We conducted two 16-day river trips (July and October 1998) to ground-truth the photo-images, allowing us to generate actual area estimates for each backwater.

Backwater availability varied considerably by geomorphic reach and by flow. Backwater number and area were greatest in wide reaches, and sand-based backwaters were virtually non-existent in narrow reaches. Backwater number and area decreased sharply at flows above 10,000 cfs, as channel margin sites were inundated. Larger return current channel backwaters were often difficult to detect on these images, and 12 of such sites have been analyzed using a void volume analysis by Northern Arizona University Geology Department staff from the sand bar monitoring program.

Using videography collected during steady research flows of approximately 8,000 cfs, our preliminary analyses indicate that the number of backwaters has increased over the course of Interim Flows and ROD flows. The number of backwaters increased from 71 in 1991 to 109 in pre-flood 1996, to 164 post-flood 1996, and continued to increase to175 backwaters in 1997. High flows during the ROD period may have permitted increased backwater formation, a finding that is consistent with the limited understanding of how these channel margin features develop. We are still analyzing the different geomorphic settings in which backwater develop, including channel margin, return current channel, and tributary mouth settings.

In contrast to backwater number, our preliminary analyses indicate that the area of backwaters has decreased over the 1990's. A 2.3-fold increase in total backwater area occurred as a result of Reclamation's 1996 Experimental Flood (from 6.1 to 14.0 ha); however, these changes were ephemeral, and backwater area decreased to 2.4 ha within 6 months and had not recovered in 1997.

We found 6 change responses of individual backwater area through the 1990's. Of the 561 backwaters detected from the aerial videography, a 193 (34.4% of the total) remained essentially unchanged from 1991 through 1997 (Table 4). A total of 147 (26.2%) displayed a unimodal response through time (increase-then-decrease). A total of 112 (20.0%) of the backwaters only substantially increased in area as a result of the 1996 test flood, and all subsequently decreased in area, most to near zero area by September 1997. In addition, another 23 (4.1%) displayed a complex, double modal pattern, increasing in area over the interval from 1991 through 1995, and then increasing more as a result of the 1996 test flood, but subsequently decreasing in area. Most of these were small or were not formed under low flows. A total of 46 (8.2%) backwaters increased in area, while 38 (6.8%) decreased in area. The frequency of change varied significantly between these categories, with fewer than expected backwaters that increased or decreased in area, and more than expected having a complex unimodal or bimodal pattern of change ($X^2_5 = 130.2, p < 0.0001$). We are conducting multivariate analyses to determine if any flow or sediment transport factors are correlated with the distribution of these change patterns.

Despite the late arrival of the funding, and interuption of work by failure of the GCMRC MIPS program (necessitating remeasuring 6 video runs), we anticipate completing this project on schedule.

INTRODUCTION

Native fish populations in the Colorado River downstream from Glen Canyon Dam have declined as a result of habitat alteration, cold-stenothermic releases from Glen Canyon Dam, blocked migratory routes, and introduction of non-native fish species and fish diseases (Minckley 1991). Recruitment failure has been identified as a key source of mortality for endangered humpback chub, as well as other native species, and has been attributed both to predation and to inhospitable mainstream habitats (Valdez and Ryel 1997). The recruitment niche for most young, native fish includes safe rearing sites with low velocity and warm (>16°C) water temperature. These refugial conditions exist downstream from Glen Canyon Dam in some Colorado River backwaters, which provide low-velocity, near-shore habitats that may warm substantially above the cold stenothermic temperature of the mainstream.

In Grand Canyon, persistent backwaters primarily form in return current channels (RCCs) associated with reattachment bars (Schmidt and Graf 1990), as well as ephemeral, near-shore habitats and cobble bar pools. RCC, and therefore backwater, density/km varies between the 13 bedrock-defined reaches of the Colorado River, with the highest density of backwaters in the widest, lowest gradient river reach. McGuinn-Robbins (1997 unpublished) reported up to 5.4-fold greater backwater density/km in wide versus narrow geomorphic reaches. RCCs open upstream and extend downstream. These backwaters differ from those found in the Upper Colorado River Watershed (e.g., Green River), which typically form on the downstream side of an eddy current and extend upstream. Green River backwaters have been documented as habitats that are widely used by native and introduced fish as nurseries, resting areas and spawning areas (Holden 1973). Fish surveys in Grand Canyon over the past decade support the hypothesis that backwaters are extensively used by native and non-native young fish (Maddux et al. 1987, Valdez and Ryel 1997; AGFD 1996).

The maintenance and rejuvenation of backwater habitats has been identified as a critical management element for Glen Canyon Dam by the Glen Canyon Dam Environmental Impact Statement (GCD-EIS, Bureau of Reclamation 1995). The recommendation regarding backwater habitats in GCD-EIS is based on the assumption that native, endangered fish require backwaters in Grand Canyon for survival. Understanding the interactions between backwater morphology and availability, and dam operations, is essential if habitat management for native, including endangered, fish species is to be improved. Elements that are key to improving this understanding include determining: (1) whether the morphology and volume of individual backwaters change in a predictable fashion across the local stage-discharge relationship; (2) determining whether reach-based and system-wide patterns of stage-related change exist; and (3) whether changes in backwater morphology have occurred over post-dam time in relation to sediment transport.

Colorado River backwaters in Glen and Grand canyons are strongly influenced daily and short-term flow fluctuations. McGuinn-Robbins (1997) reported that between 70 and 146 backwaters $\geq$100 m^2 existed along the Colorado River from Lees Ferry to Diamond Creek in 1990-1995. She found that mean backwater area increased 1.4-fold from a mainstream flow of 142 m^3/s to 227 m^3/s, and then decreased at a flow of 425 m^3/s. Unfortunately, this research was reach-based, and did not focus on whether such changes were consistent among all backwater habitats within each reach. This is important because the spatial habitat scale most relevant to a young fish is that of an individual backwater. Young fish may not be able to tolerate the increased velocity and decreased temperature if that backwater is flushed by high, cold mainstream flows. Stage-related area analyses of individual backwaters, and changes of individual backwater area and volume over time are being conducted through this project for the first time. These analyses will greatly improve the state of knowledge regarding Grand Canyon backwater habitat availability, and relationships to dam operations.

Colorado River RCCs and other backwaters undergo terrestrialization, through aggradation of tributary-derived sediments and development of marsh and woody vegetation (Stevens et al. 1995). RCCs develop under high discharges (Schmidt and Graf 1990), and change in area, volume and availability as a function of river stage. In the absence of scouring flows, RCCs aggrade over a period of several years as tributary-derived fine sediments are deposited in them. Fine sediments in backwaters provide appropriate germination sites for wetland plant species, and RCCs are gradually transformed into marshes and, later, terrestrial woody plant communities (Stevens et al. 1995). Therefore, backwater habitat area and availability may change over hourly to decadal time scales in this regulated river ecosystem.

Flood flows are required to reverse backwater terrestrialization, and Stevens et al. (1995) predicted that flows greater than 1275 m^3/s were required to rejuvenate RCC backwaters. McGuinn-Robbins (1997 unpublished) reported a long-term decline in backwater habitat availability from 1984 to 1995; however, she found that mean backwater area did not vary between years from 1990 and 1995, except in 1992 when mean area decreased slightly. This conclusion was based on a reach-based assessment, rather than on analysis of individual backwaters. The hypothesis that high flows are needed to rejuvenate backwaters was tested during the Bureau of Reclamation's week-long, 1274 m^3/s Experimental Flood from Glen Canyon Dam in March 1996. While this flood successfully restored and created numerous sand bars, it reportedly failed to scour and rejuvenate RCC backwaters. To date, there has been no detailed analysis of backwater changes associated with that Experimental Flood, individual backwater morphology changes have not been monitored, and backwater volume has not been related to local stage and discharge and local sediment input, except at three sites monitored by Parnell et al. (1997).

Determining relationships between mainstream discharge, tributary sediment inflow, and rates of RCC aggradation are critical elements that need to be defined for management of the Colorado River ecosystem. Backwaters are a major link between physical and the aquatic and terrestrial components of the Colorado River ecosystem. Understanding the dynamics that exist among mainstream flow and backwater habitat availability will assist in future management decisions concerning the availability of these habitats, and the timing and duration of habitat maintenance and habitat building flows. In addition, determining whether consistent stage-related patterns of habitat availability exist is important to determine the timing of flows. A seasonally-adjusted steady flow regime has been proposed by the U.S. Fish and Wildlife Service for this river ecosystem to benefit native fish; however, stage-related distribution patterns of backwater habitats should be thoroughly understood before such a flow regime can be conducted to benefit the native fish assemblage.

Thus, backwaters may serve as important nursery habitats for young native and non-native fish in the Colorado River downstream from Glen Canyon Dam; but changes in backwater habitat availability have not been examined at the scale of individual backwaters that is relevant to young fish. Neither has there been an analysis of how the area and volume of individual Colorado River backwaters has changed over a range of mainstream and tributary flows. contributions and discharge. We are addressing these questions using existing photography and topographic data to fill this important information gap.

Despite the late arrival of the funding, and interuption of work by failure of the GCMRC MIPS program (necessitating the remeasurement of 6 video runs), we anticipate completing this project on schedule.

OBJECTIVES

We are using Bureau of Reclamation aerial photographs and videography from 1965 to 1997 to analyze changes in the area of individual backwaters across stage and over time. For selected sites where long-term topographic monitoring are available, we are using Northern Arizona University Department of Geology survey data, and Arizona Game and Fish Department survey data, to determine changes in backwater hypsometry (volume as a function of stage) over time. These analyses are providing a greatly improved understanding of the changing availability of backwater habitats within and between geomorphic reaches, and on a system-wide basis. Our specific objectives included the following:

1) Determine whether Colorado River backwaters $\geq 100 m^2$ in area and detectable from aerial photography or videography,have changed over time, from 1965 to 1997 (imagery permitting), and whether reach-based and system-wide patterns of change exist.

2) Determine how the area of each individual Colorado River backwater $\geq 100 m^2$ in area changed across the stage-discharge relationship in the early 1990's and the late 1990's, and compare these two time periods in relation to individual backwater, reach-based and system-wide patterns of change.

3) Determine whether the volumetric hypsometry (volume as a function of stage elevation) of selected large, characteristic Colorado River backwaters has changed from 1990 to 1997, and whether such changes are related to tributary or mainstream flow.

The intent of this research is to determine backwater habitat availability at the scale of individual backwaters, during post-dam time, and across a wide range of flows (8,000 cfs - 45,000 cfs). In addition, this study is producing an assessment of the rate volumetric change at selected backwaters from 1990 through 1997 in relation to mainstream and tributary sediment transport. Importantly, this latter analysis is indicating the extent to which backwater aggradation and terrestrialization is a predictable consequence of mainstream sediment transport. This project will not improve understanding of native fish use of backwaters, but it will provide a new, thorough understanding of backwater habitat availability through space and time.

METHODS

Objective 1: Determine whether the area of each individual Colorado River backwater $\geq$100m^2 in area and detectable from aerial photography or videography has changed over time, from 1965 to 1997 (imagery permitting), and whether reach-based and system-wide patterns of change exist.

We compiled data on backwater distribution and characteristics in relation to flow of the Colorado River, using Bureau of Reclamation videography and fixed-wing photo imagery of the Colorado River corridor from 1965 (analyses still underway) through 1997 (Table 1). In many cases, the flows were held steady during these photography runs, providing an excellent opportunity to measurement of backwater characteristics. In a few cases, the flow varied slightly during photo runs; for those runs we used the mean flow during the run as our flow estimate.

We used a Map Image Processing Software (MIPS) program to determine backwater areas from videography and still photography (analyses still underway) for Grand Canyon (Table 1). Individual backwaters were identified and the best frame was captured from the available images on each run. Mr. David Baker (AGFD) measured each backwater's area, mouth width, length, maximum width and shoreline perimeter three times each using MIPS. We used the mean of these three measurements for all analyses. We named and georeferenced backwaters by identifying them on a single comprehensive set of aerial photographs, which is maintained by AGFD.

We are documenting mapping error associated with each backwater characteristic at each detected site and for each aerial photography run. Each measurement was made three times, and we used the mean for statistical analyses. To estimate mapping error, we are calculating the variance for each measurement at each backwater for each run. We are then calculating the mean measurement variance for all linear and all area measurements. The variance of one-dimensional measurements should be proportional to the standard deviation of area (two dimensional) measurements. We are also comparing individual mean length variance against the corresponding standard deviation of area measurements to back-check the consistency of this error assessment.

We ground-truthed the aerial photo imagery by establishing up to three ground control points (GCPs) around each of 30 backwaters and compared remotely measured distances to GCP measurements at these sites for each run. We performed simple linear regression analysis and evaluated the coefficient of determination (r^2) and F-statistic to determine whether or not to estimate actual area from MIPS measurements.

Repeated constant flows of 8,000 cfs (226 m^3/s) have been conducted for the purpose of documenting river corridor conditions since 1990. As an initial analysis, we conducted an initial assessment of trends in each backwater photographed at this stage as a function of Julian day since 1990. These analyses provide a general history of each habitat. We expect to see a decrease in backwater area from 1990 through 1997, as backwaters filled with sediment during interim (low hourly fluctuation) flows. We are analyzing these data using the non-parametric Friedman test, with years as treatments and individual backwaters as replicates. This analysis is determine whether differential aggradation and loss of backwaters has occurred upstream from the Little Colorado River over that time period, and whether there was punctuated reduction in backwater habitat area downstream in relation to tributary flooding in January and February

1993.

Reach-based and system-wide analyses of backwater number and area were developed by pooling all individual backwater data from each geomorphic reach (Schmidt and Graf 1990 and Stevens et al. 1997). These data were compiled, and graphically analyzed, with 95% confidence limits for each backwater characteristic by reach and photograph run.

Table 1: Aerial photography analyzed to date from the Colorado River corridor in Grand Canyon (stored at GCMRC in Flagstaff, AZ).

Run Type	Date	Q (cms)	JDay
Video	910519	142	139
Video	911003	241	307
Video	920504	255	490
Video	920707	415	553
Video	930530	227	881
Video	930706	415	918
Video	940530	227	1246
Video	950528	227	1609
Video	950808	538	1681
Video	960123	467	1849
Video	960324	227	1909
Video	960330	1274	1915
Video	960407	227	1923
Video	960621	510	1998
Video	960902	227	2071
Video	970221	765	2244
Video	970420	595	2302
Video	970901	227	2436
Video	971105	867	2500
Video	971107	623	2502

Cumulative sediment transport and effective discharge are being calculated for each measurement, using the techniques of Schmidt and Rubin (1995), and these data are being used to test whether, and to what extent, tributary contribution of suspended sediment loads are related to aggradation rates of individual backwaters.

Objective 2: Determine how the area of each individual Colorado River backwater ≥100m^2 in area changed across the stage-discharge relationship in the early 1990's and the late 1990's, and compare these two time periods in relation to individual, reach-based and system-wide patterns of change.

We have collected, or measured from videography and still photography images, the area of each detectable backwater through the river corridor at discharges of 141, 226 and 425 m3/s in 1990-1991, and at discharges of 226, 556,765, 878, 1275 m^3/s in 1996-1997. We are developing a backwater area to stage-discharge relationship for each backwater for both time periods, and compare the curves. As in Objective 1 (above), we predicted that periods of greater tributary discharge (compiled in Objective 1) would result in more rapid aggradation of backwaters. We are developing mean, reach-based and system-wide rates of area reduction using individual backwater data over time. From these compilations, we are determining the rates of backwater area change in relation to sediment inflow and mainstream stage, and we are attempting to generate a predictive regression model of this process.

Objective 3: Determine whether the volumetric hypsometry (volume as a function of stage elevation) of selected large, characteristic Colorado River backwaters has changed from 1990 to 1997, and whether such changes are related to tributary or mainstream flow.

We are conducting hypsometric analysis of 20 large RCC backwaters that have been surveyed by the Kaplinski et al. (1997) since 1990. These sites include: -6.5R, 3L, 22R, 30L, 43L, 44.4L, 50L, 51.5L, 55.5R, 68R, 104R, 119L, 122R, 123L, 136L, 145L, 172L, 183R, 194L, and 225R. These sites have been used to measure sand bar erosion, but volumetric hypsometry of their RCC backwaters has never been analyzed. Semi-annual topographic and bathymetric surveys have been conducted at these sites since 1990, resulting in approximately 16 surveys per site at an accuracy of approximately 10 cm. All sites have a well-documented stage-to-discharge relationship, and all sites are reattachment bars (*sensu* Schmidt and Graf 1990). Ground-based and bathymetric survey points are combined for each site to form a triangulated irregular network (TIN) surface model. This procedure is performed using Sokkia Mapping Software (Datacom Software Research Limited 1992). Breaklines were coded during data collection, and are used to force individual triangle sides along the proper grade breaks in order to prevent incorrect interpolations across the surface. Topographic survey accuracy is <10 cm, and the TIN model is contoured at 20 cm intervals.

RCC backwater volumes were calculated against the local stage-to-discharge relationship at each site. Elevation intervals are set at 100 m^3/s stages between 150 and 1275 m^3/s, depending on data availability. The resulting volume-to-discharge curves are linearized and modeled, or non-linearly modeled, and analyzed over time to determine rate of volumetric change. Slope coefficient (rate of change) for each site are graphed and regressed over time to evaluate whether patterns of hypsometric change at individual RCCs are consistent within reaches. Sediment transport and effective discharge are being analyzed over this time period at each site to determine whether any relaionship exists between backwater aggradation rate, tributary sediment contribution and mainstream discharge. We are conducting a stepwise multiple regression using the hypsometric slope coefficient as a response variable, and several predictor variables, including: the estimated cumulative sediment transported during interval associated with the sand bar survey; mainstream discharge variables; and location for all sites combined, as well as for the nine sites lying in the sediment starved section between Glen Canyon Dam and the Little Colorado River (km 98), and the 11 sites lying between km 98 and Diamond Creek.

RESULTS AND DISCUSSION

Objective 1: Determine whether the area of each individual Colorado River backwater $\geq$100m^2 in area and detectable from aerial photography or videography has changed over time, from 1965 to 1997 (imagery permitting), and whether reach-based and system-wide patterns of change exist.

Error Analysis: To determine whether or not backwater number or area changed during the 1990's, we analyzed aerial photography runs, particularly focusing on runs when flows were held steady at approximately 226 m^3/s.

We are presently engaged in error assessment calculation and will present variance for each triple measurement of each backwater characteristic at each site and for each run in the draft final report.

We adjusted MIPS measurements using the simple linear regression model of the relationship between MIPS measurements and ground-truthed measurements for each run separately (Table 2). In all cases, these relationships were tightly correlated and highly significant. Therefore, this adjustment provides an appropriate estimate of actual backwater area, within the level of resolution allowed by the above error analysis.

Changing Backwater Number: Contrary to our original expectations, preliminary analyses indicate that the number of backwaters showed a decrease in the early, low-water phase of Interim Flows (1991-1994), and then increased under higher flows from 1995 to 1997 (Table 3). Using the 8,000 cfs steady flows videography, only 71 backwaters were detectable from the October 1991 videography, a number which remained low in 1993 (41 backwaters) and 1994 (61 backwaters), but which reached a total of 150 backwaters in September 1996 and 175 backwaters in August 1997. The 1996 experimental flood increased backwater number from 109 on 24 March 1996 to 164 on 6 April 1996, a 1.5-fold increase in number. Backwater number increased further in late 1996 and late 1997, as indicated above, with a 1.6-fold increase in backwater number in August 1997 above the pre-March 1996 period.

Table 2: Preliminary comparison of ground-truthed measurement with mean (n=3) MIPS measurement at the same 20 points for all aerial photography runs, 1991-1997. Date, discharge (Q in m^3/s) is given, the simple linear regression slope coefficient between measured GCP's and MIPS measurements, and the y-intercept are presented. Standard simple linear regression statistics are provided.

Date	$Q(m^3/s)$	Slope Coefficient MIPS=X(map units)	Constant (Y-Intercept)	R^2	F	*P*	Df
5/19/91	141.6	0.3542	1.7035	0.801	49.181	<0.0001	1,11
10/3/91	240.7	0.368	1.4068	0.752	43.409	<0.0001	1,13
5/4/92	254.9	0.3041	1.3599	0.861	125.07	<0.0001	1,19
7/7/92	414.8	0.3185	0.6263	0.926	237.71	<0.0001	1,18
5/30/93	226.5	0.3469	0.5302	0.956	1032.6	<0.0001	1,16
7/6/93	414.4	0.4454	0.1249	0.917	222.13	<0.0001	1,19
5/30/94	226.5	0.7045	0.4356	0.92	243.18	<0.0001	1,20
5/28/95	226.5	0.4531	0.4189	0.91	202.92	<0.0001	1,19
8/8/95	538.0	0.4208	0.9308	0.828	87.68	<0.001	1,17
1/23/96	467.2	0.4088	0.7496	0.861	106.20	<0.001	1,16
3/24/96	226.5	0.4119	0.9714	0.86	124.10	<0.0001	1,19
3/30/96	1274.3	0.4047	0.8246	0.953	244.83	<0.0001	1,11
4/7/96	226.5	0.3767	1.1575	0.826	95.75	<0.0001	1,19
6/21/96	509.7	0.3914	0.9779	0.771	64.99	<0.001	1,18
9/2/96	226.5	0.3888	1.4211	0.882	150.99	<0.0001	1,19
2/21/97	764.6	0.4188	0.7265	0.889	129.53	<0.0001	1,15
4/20/97	594.7	0.4462	0.1601	0.937	223.55	<0.0001	1,14
9/1/97	226.5	0.421	0.6234	0.91	202.79	<0.0001	1,19
11/5/97	877.8	0.4251	0.9765	0.926	126.90	<0.0001	1,9
11/7/97	623.0	0.4233	0.7347	0.958	273.90	<0.0001	1,11

Table 3: Backwater area (ha), cover (ha/km), number and density (no./km) from videography runs, by geomorphic reach (Schmidt and Graf 1990, Stevens et al. 1997), Glen Canyon Dam to Diamond Creek, Arizona, 1991-1997.

Flow (cfs): Date: Reach		5000 5/19/91	6-11,000 10/3/91	8-10,000 5/4/92	11-18,300 7/7/92	8000 5/30/93	14.57-14.7 7/6/93	8000 5/30/94	8000 5/28/95	19000 8/7/95	14-19k 1/23/96
Glen Canyon	Area (ha)	1.54	0.04	1.45	2.15	1.78	3.63	7.36	2.82	4.37	0.00
	Cover (ha/km)	0.06	0.00	0.06	0.08	0.07	0.14	0.29	0.11	0.17	0.00
	Number	12.00	2.00	5.00	4.00	6.00	4.00	6.00	6.00	5.00	0.00
	Density (n/km)	0.47	0.08	0.20	0.16	0.23	0.16	0.23	0.23	0.20	0.00
Permian	Area (ha)	0.19	0.09	0.27	0.00	0.22	0.00	1.07	0.31	0.00	0.15
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	7.00	4.00	1.00	0.00	1.00	0.00	4.00	2.00	0.00	3.00
	Density (n/km)	0.42	0.24	0.06	0.00	0.06	0.00	0.24	0.12	0.00	0.18
Supai	Area (ha)	0.14	0.04	0.00	0.00	0.01	0.00	0.11	0.02	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	5.00	2.00	1.00	0.00	1.00	0.00	2.00	1.00	0.00	0.00
	Density (n/km)	0.27	0.11	0.05	0.00	0.05	0.00	0.11	0.05	0.00	0.00
Redwall	Area (ha)	0.13	0.02	0.00	0.00	0.01	0.02	0.15	0.07	0.09	0.04
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	7.00	2.00	0.00	1.00	1.00	2.00	3.00	5.00	1.00	2.00
	Density (n/km)	0.25	0.07	0.00	0.04	0.04	0.07	0.11	0.18	0.04	0.07
Marble Cyn	Area (ha)	1.34	0.53	0.57	0.52	0.47	0.36	5.51	1.03	0.30	0.16
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	37.00	22.00	22.00	14.00	12.00	4.00	23.00	14.00	2.00	1.00
	Density (n/km)	1.08	0.64	0.64	0.41	0.35	0.12	0.67	0.41	0.06	0.03
Furnace Flats	Area (ha)	0.36	0.05	0.11	0.01	0.32	0.32	0.95	0.40	0.11	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	12.00	3.00	2.00	1.00	8.00	5.00	6.00	9.00	2.00	0.00
	Density (n/km)	0.46	0.12	0.08	0.04	0.31	0.19	0.23	0.35	0.08	0.00

Up.GraniteGrg	Area (ha)	0.24	0.01	0.22	0.00	0.13	0.05	0.69	0.11	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	10.00	1.00	4.00	0.00	4.00	2.00	5.00	4.00	0.00	0.00
	Density (n/km)	0.15	0.02	0.06	0.00	0.06	0.03	0.08	0.06	0.00	0.00
Aisles	Area (ha)	0.13	0.05	0.02	0.08	0.00	0.00	0.05	0.01	0.22	0.02
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	7.00	2.00	1.00	8.00	0.00	0.00	1.00	1.00	2.00	1.00
	Density (n/km)	0.56	0.16	0.08	0.65	0.00	0.00	0.08	0.08	0.16	0.08
Mid Gran Grg	Area (ha)	0.01	0.01	0.00	0.00	0.02	0.01	0.06	0.06	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	1.00	1.00	0.00	0.00	1.00	1.00	1.00	2.00	0.00	0.00
	Density (n/km)	0.04	0.04	0.00	0.00	0.04	0.04	0.04	0.09	0.00	0.00
Muav	Area (ha)	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	1.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00
	Density (n/km)	0.03	0.00	0.00	0.03	0.00	0.03	0.00	0.00	0.00	0.00
Low Grand Cyr	Area (ha)	1.82	0.53	0.22	0.15	0.27	0.38	1.15	1.53	0.10	0.49
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	59.00	31.00	11.00	10.00	6.00	10.00	9.00	28.00	2.00	11.00
	Density (n/km)	0.68	0.36	0.13	0.12	0.07	0.12	0.10	0.32	0.02	0.13
Low Gran.Grg	Area (ha)	0.00	0.01	0.00	0.03	0.00	0.04	0.23	0.07	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	0.00	1.00	0.00	1.00	1.00	1.00	1.00	3.00	0.00	0.00
	Density (n/km)	0.00	0.05	0.00	0.05	0.05	0.05	0.05	0.16	0.00	0.00
Total	Area (ha)	5.89	1.37	2.87	2.94	3.23	4.81	17.33	6.43	5.20	0.87
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	158.00	71.00	47.00	40.00	41.00	30.00	61.00	75.00	14.00	18.00
	Density (n/km)	0.41	0.18	0.12	0.10	0.11	0.08	0.16	0.19	0.04	0.05

Flow (cfs):		8000	45000	8000	16-20k	8000	8000	27000	21000	31000	21-23,000
Date:		3/24/96	3/29/96	4/6/96	6/22/96	8/31/97	9/1/96	2/20/97	4/19/97	11/4/97	11/6/97
Reach											
Glen Canyon	Area (ha)	0.83	0.21	2.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cover (ha/km)	0.03	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	3.00	1.00	7.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Density (n/km)	0.12	0.04	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Permian	Area (ha)	0.09	0.13	0.67	0.11	0.26	0.17	0.03	0.05	0.00	0.01
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	4.00	3.00	4.00	3.00	8.00	3.00	2.00	2.00	0.00	1.00
	Density (n/km)	0.24	0.18	0.24	0.18	0.48	0.18	0.12	0.12	0.00	0.06
Supai	Area (ha)	0.07	0.14	0.35	0.00	0.06	0.01	0.01	0.00	0.00	0.02
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	3.00	3.00	4.00	0.00	10.00	2.00	1.00	0.00	0.00	1.00
	Density (n/km)	0.16	0.16	0.22	0.00	0.54	0.11	0.05	0.00	0.00	0.05
Redwall	Area (ha)	0.21	0.11	0.81	0.03	0.04	0.15	0.03	0.02	0.01	0.21
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	3.00	1.00	15.00	3.00	6.00	18.00	2.00	2.00	1.00	2.00
	Density (n/km)	0.11	0.04	0.53	0.11	0.21	0.64	0.07	0.07	0.04	0.07
Marble Cyn	Area (ha)	1.10	0.02	3.44	0.71	0.69	0.54	0.37	0.05	0.19	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	21.00	1.00	42.00	16.00	43.00	32.00	11.00	2.00	6.00	0.00
	Density (n/km)	0.61	0.03	1.23	0.47	1.26	0.94	0.32	0.06	0.18	0.00
Furnace Flats	Area (ha)	0.28	0.02	1.10	0.18	0.30	0.25	0.04	0.02	0.00	0.09
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	4.00	1.00	15.00	4.00	21.00	13.00	2.00	1.00	0.00	3.00
	Density (n/km)	0.15	0.04	0.58	0.15	0.81	0.50	0.08	0.04	0.00	0.12
Up.GraniteGrg	Area (ha)	0.60	0.11	0.69	0.03	0.19	0.16	0.06	0.05	0.02	0.01
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	9.00	3.00	9.00	2.00	15.00	14.00	2.00	3.00	1.00	1.00
	Density (n/km)	0.14	0.05	0.14	0.03	0.23	0.22	0.03	0.05	0.02	0.02

Aisles	Area (ha)	0.32	0.15	0.29	0.05	0.11	0.06	0.04	0.00	0.00	0.03
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	9.00	2.00	7.00	2.00	14.00	10.00	3.00	0.00	0.00	2.00
	Density (n/km)	0.73	0.16	0.56	0.16	1.13	0.81	0.24	0.00	0.00	0.16
Mid Gran Grg	Area (ha)	0.07	0.00	0.12	0.00	0.01	0.01	0.01	0.00	0.00	0.12
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	2.00	0.00	3.00	0.00	5.00	2.00	1.00	0.00	0.00	2.00
	Density (n/km)	0.09	0.00	0.13	0.00	0.21	0.09	0.04	0.00	0.00	0.09
Muav	Area (ha)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	1.00
	Density (n/km)	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.00	0.03
Low Grand Cyr	Area (ha)	2.19	0.40	3.72	0.26	0.65	0.93	0.06	0.20	0.28	0.30
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	45.00	4.00	51.00	7.00	47.00	49.00	4.00	8.00	2.00	9.00
	Density (n/km)	0.52	0.05	0.59	0.08	0.54	0.57	0.05	0.09	0.02	0.10
Low Gran.Grg	Area (ha)	0.33	0.00	0.27	0.04	0.06	0.09	0.00	0.00	0.00	0.00
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	6.00	0.00	7.00	3.00	5.00	6.00	0.00	0.00	0.00	0.00
	Density (n/km)	0.32	0.00	0.37	0.16	0.26	0.32	0.00	0.00	0.00	0.00
Total	Area (ha)	6.09	1.29	13.95	1.41	2.37	2.36	0.64	0.38	0.49	0.78
	Cover (ha/km)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Number	109.00	19.00	164.00	40.00	175.00	150.00	28.00	18.00	10.00	22.00
	Density (n/km)	0.28	0.05	0.42	0.10	0.45	0.39	0.07	0.05	0.03	0.06

Relatively steady flows from 1994 through 1997 may be responsible for increased backwater number at a flow of 226 m3/s. The period from 1995 through 1998 has been characterized as high inflow years, with additional reduction in hourly flow variation in addition to that imposed by Interim Flows and the Preferred Alternative criteria (Bureau of Reclamation 1995). The abundance of tributary-derived sediment and high flows that rework sediment deposits stored along the channel, may influence backwater formation.

Changing Backwater Area: Preliminary analysis of patterns of backwater area change were conducted using the 1991-1997 by turning again to the videography data from 10 steady 226 m3/s flows (Table 3). In contrast to the increase in backwater number through time, the area of backwater habitats fluctuated, and generally decreased from 1991 through 1997 (Table 3). Backwater area was 1.4 to 3.3 ha in 1991-1993, and increased from 6.1 to 14.0 ha (a 2.3-fold increase) as a result of the 1996 Experimental Flood, but then decreased to 17% of that area by August 1997.

Preliminary analyses indicate that total backwater area has become increasingly influenced by flow (Table 3). Total backwater area underwent little change between flows of about 9,000 cfs to about 15,000 cfs in 1992, but sustaining an 80% reduction in area at flows of 8,000 cfs to 21,000 cfs in 1997.

Objective 2: Determine how the area of each individual Colorado River backwater ≥100m^2 in area changed across the stage-discharge relationship in the early 1990's and the late 1990's, and compare these two time periods in relation to individual, reach-based and system-wide patterns of change.

Preliminary analysis of patterns of backwater area change were conducted using the 1991-1997 by turning again to the videography data from 10 steady 226 m3/s flows. We categorized each of 561 backwaters as to whether they: (1) increased in area; (2) decreased in area; (3) displayed a unimodal increase-then-decrease in area; (4) only substantially increased in area as a result of the 1996 test flood (subsequently decreasing in area); (5) displayed a complex, bimodal pattern (a mid-1990's increase and a rejuvenation by the 1996 test flood), returning to low area by 1997; or (6) remained basically unchanged during the period of study. We based this evaluation on whether individual backwaters had changed in area by more than 50 m^2, as well as whether the direction of change was consistent for more than one measurement run.

This analysis revealed that of the 561 backwaters detected from the aerial videography, a 193 (34.4% of the total) remained essentially unchanged from 1991 through 1997 (Table 4). A total of 147 (26.2%) displayed a unimodal response through time (increase-then-decrease). A total of 112 (20.0%) of the backwaters only substantially increased in area as a result of the 1996 test flood, and all subsequently decreased in area, most to near zero area by September 1997. In addition, another 23 (4.1%) displayed a complex, double modal pattern, increasing in area over the interval from 1991 through 1995, and then increasing more as a result of the 1996 test flood, but subsequently decreasing in area. Most of these were small or were not formed under low flows. A total of 46 (8.2%) backwaters increased in area, while 38 (6.8%) decreased in area. The frequency of change varied significantly between these categories, with fewer than expected backwaters that increased or decreased in area, and more than expected having a complex unimodal or bimodal pattern of change ($X^2_5 = 130.2, p < 0.0001$).

Table 4: Summary of patterns of change of Colorado River backwaters detected on aerial videography, 1990-1997, including: number, percent of total, mean maximum size (m^2) and 1 sd, mean individual backwater area change (m2) and 1 sd. See text for a detailed description of change categories.

Change	Number	%of BWs	Mean Max A m2	Sd Max A m2	Mean Mean A m2	1 sd Mean A m2	Mean Percent Mean/Max Ratio
No Change	193	34.4	102	294.7	11	33.2	5.13
Modal	147	26.2	961	2473.8	159	492.7	15.00
Flood	112	20.0	900	1524.0	155	376.7	14.22
Increase	46	8.2	980	4054.3	173	742.6	12.14
Decrease	38	6.8	817	1667.3	151	253.7	20.64
Bimodal	23	4.1	1262	1503.0	235	251.3	20.29
Unknown	2	0.4	1063	1381.0	176	235.5	13.96
Total	561	100.0	661	1962.9	111	385.3	11.82

Objective 3: Determine whether the volumetric hypsometry (volume as a function of stage elevation) of selected large, characteristic Colorado River backwaters has changed from 1990 to 1997, and whether such changes are related to tributary or mainstream flow.

Understanding the interactions between backwater morpholoy and availability and dam operations is essential if management actions are intended to improve habitat for endangered native fish species. We are examining this concept through hypsometric analysis of backwater morphology that existed at selected reattachment bar study sites during the monitoring period (1991-1998). We are testing whether or not backwaters have responded to different river flow regimes and sediment transport. Individual backwater morphology was examined at selected sites from as many as 15 surveys over a 7 year period. Topographic models of the bar and RCC surface were utilized for volume calculations.

Preliminary results of the RCC volume data during each run were compiled into a time series to examine temporal trends in backwater morphology. The total RCC volume at all stage elevations was normalized by expressing each volume measurement as the percent of the post-1996 BHBF measurements. These analyses suggest that total RCC volume declined during interim flows and that the 1996 BHBF did not effect the total volume significantly (Fig. 1). These data suggest that the restricted flows characteristic of the interim operating criteria resulted in a decrease in the area (consistent with the system-wide MIPS analyses in Objective 1, above), and the volume of these large, well-established RCCs. In general, the 1996 BHBF did not scour backwaters and, as a result, the total RCC volume does not reflect a significant increase in the size and area of RCC backwaters. However, high flow regimes in 1997 and 1998 (20,000 to 27,000 cfs) increased the average RCC volume and have slightly reversed the decreasing trend in

RCC volume. This analysis is preliminary and the completion of more sites in the analysis will provide greater resolution of changing backwater volume through time.

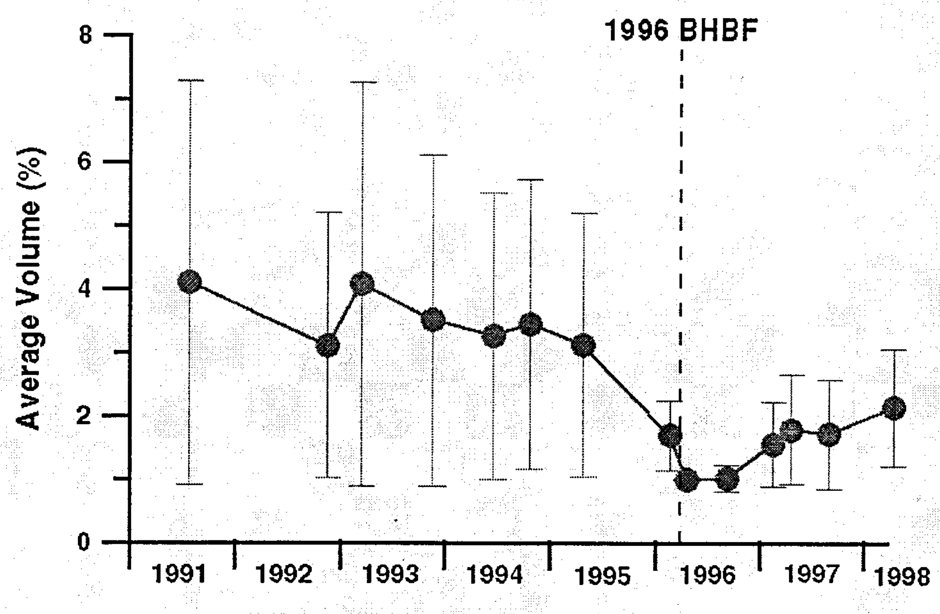

Figure 1. Average total RCC volume for 12 sites, normalized to the post-1996 BHBF measurement versus time. Error bars are ± 1 se.

Expected Final Results/Products

We are analyzing all backwater characteristics and all available data on volume changes from 1965 through 1997. The final report will provide a definitive interpretation of changes in backwater habitat availability on the basis of change among individual backwaters, and related to Glen Canyon Dam operations. We are modeling the rate of hypsometric backwater volume change over time and in relation to sediment transport. The final report will be prepared for peer-reviewed submission to a scientific journal, such as *Regulated Rivers: Research & Management.*

Information Transfer/Data Archiving Plan

All data are being compiled and quality controlled by reviewing each data entry, and by conducting an outlier analysis. Mapping error analyses will be presented and summarized for each site. Data and metadata will be presented to GCMRC in hard copy and ASCII format on disk with the final report.

Timetable for Project including Schedule for Interim and Final Reports

Actual work on this project began in June 1998, and because of this delay we intend to submit the draft final report on or before 31 March 1999. The final report will be submitted on or before 31 March 1999, with a

Summary of Expenditures

The budget requested for this project was $46,146.00 for 15 months, and includes partial salaries for Dr. Hoffnagle (5% FTE, $2000), one year of support for Mr. David Baker ($19,000+ERE), and 6 months for Mr. Jeff Bennett of the NAU Geology Department ($11,908 + $5668 ERE + 20% NAU overhead). Dr. Stevens salary is covered by ATA, Inc./GCMRC. Approximately 10% of his FTE is used for this project.

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