HISTORICAL VEGETATION PATTERNS ALONG THE COLORADO RIVER IN GRAND CANYON: A PROPOSAL TO IDENTIFY LARGE SCALE AND SPECIES-SPECIFIC TRENDS

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The process of damming rivers can create riparian habitat (Nagel and Dart 1980, Turner and Karpiscak 1980; Waring 1993). This could be useful today as more than 50% of this relatively rare, productive habitat has been lost in the western United States (Dahl 1990, Knopf et al. 1988, Simcox and Zube 1985, Brown et al. 1977). Riparian vegetation studied along stretches of the Colorado River in the upper Grand Canyon increased more than 160% following river regulation (Waring 1996). This was despite extensive post-dam flooding during the early 1980's that reduced vegetation in some areas by more than 20% (Stevens and Waring 1988). With proper management, dams may help to mitigate to some extent the loss of riparian habitat that has occurred due to other human activities.

While vegetation may increase along dammed rivers, equally important details such as the structure of the plant communities that develop and other environmental conditions that influence their development remain poorly understood (Waring 1993). This type of information is essential to sustain the productivity and diversity of these valuable habitats. Most studies of plant responses to impoundment focus on *either* single plant species (e.g., Knopf and Scott 1990, Rood and Mahoney 1990, Akashi 1988) *or* whole communities (e.g., McDonald and Sidle 1992), without considering both. Furthermore, few existing studies of impoundment effects on riparian vegetation consider the effects of different kinds of dam operations on vegetation: most emphasis is placed on the effects of initial river regulation.

This study addresses the impacts of river regulation on community-wide and species-specific levels, by examining changes in cover of riparian vegetation on a large scale, and with a detailed examination of the changing demographics of a single riparian tree species, Goodding willow (*Salix gooddingii).*

The Colorado River in Grand Canyon has been dammed for more than 30 years. Prior to the construction of Glen Canyon Dam, little vegetation persisted in the riparian corridor due to frequent flooding (Waring 1996, Turner and Karpiscak 1980, Clover and Jotter 1944). Subsequent to the completion of the dam, an extensive and diverse community of riparian plants and animals has become established along the river in the 'New High Water' zone (e.g., Stevens and Waring 1988, Warren and Schwalbe 1988, Brown and Johnson 1988, Pucherelli 1986, Turner and Karpiscak 1980, Carothers and Aitchison 1976, Martin 1971). The riparian vegetation of the 'Old High Water' zone (OHW), comprised mainly of honey mesquite (*Prosopis glandulosa)* and catclaw acacia (*Acacia greggii)*, has not been as dramatically affected by river regulation (Waring 1996).

Use of aerial photography analysis in Grand Canyon has enabled quantification of large-scale change in riparian vegetation coverage along the Colorado River over a 20 year period (1965-1985) (Pucherelli 1986). Pucherelli quantified the influence of the completion of Glen Canyon Dam, and post-dam floods in 1983 and 1984 on riparian vegetation cover, finding that NHW vegetation cover increased significantly along the Colorado River from 1965 until extensive post-dam flooding in 1983-1984, during which NHW vegetation cover decreased dramatically.

Colorado River flow patterns have been altered again in an attempt to reduce beach erosion throughout the river corridor. The interim flow regime, implemented in 1991, was designed to minimize daily fluctuations in Colorado River flows.

The primary objective of this research was to investigate the impact of river regulation on riparian vegetation in the lower Grand Canyon, by studying changes in vegetation following the impoundment event itself and subsequent dam operations. I determined historical patterns of riparian vegetation cover in the NHW zone and the OHW zone between 1965 to 1992; I measured responses of riparian vegetation to the completion of Glen Canyon Dam, the flood years of 1983-1984 and interim flows between 1990 and 1992. An historical analysis of vegetation cover in geographic information systems (GIS) reaches, through events such as the completion of Glen Canyon Dam and floods in 1983 and 1984, provides an important context from which to consider interim flow effects as well as future conditions.

This research compares vegetation coverage along the river cover one year before and one year after the initiation of the current ‘interim’ flow regime. Analysis of the extent of riparian vegetation cover with aerial photography provides a test of the ability of interim flows to minimize resource losses. A finding of stable or increased vegetation cover in the NHW zone will support this assumption about interim flows.

Photogrametric analysis will document vegetation responses to interim flows. Apparently, interim flow effects on riparian vegetation were discernible as early as Fall, 1991, within two months after interim flows began (Lawrence Stevens, personal communication, October, 1991). Specifically, clonal plants including coyote willow (*Salix exigua*) were extending their distributions closer to the river level.

Goodding willow is now most abundant in the lower Grand Canyon, where large populations have recently colonized exposed deltas that have formed at the headwaters of Lake Mead. In contrast, there is little evidence of recruitment in this specie’s upstream populations. This pattern of Goodding willow decline is opposite that of the general trend of riparian vegetation in Grand Canyon (Waring 1996). Though never wide-spread, Goodding willow was once a dominant riparian tree species in Grand Canyon (Turner and Karpiscak 1980). Its fate throughout the southwestern United States is of concern to scientists, due to extensive river regulation and other forms of habitat destruction. With a demographic study of this species it became possible to describe the status of this species in Grand Canyon.

SPECIFIC OBJECTIVES

1. Identify historical patterns of riparian vegetation cover in the NHW and OHW

zones from 1965 to 1992 in the same three reaches. Responses of riparian vegetation to the completion of Glen Canyon Dam, the flood years of 1983-1984 and subsequent recolonization patterns were quantified.

2. Measure interim flow effects on riparian vegetation cover in the new high water zone (NHW) and old high water zone (OHW) between 1990 and 1992 in three lower Grand Canyon GCES GIS reaches (#'s 8, 10 and 13). This enabled a comparison of vegetation cover one year before and one year after the initiation of this flow regime.

3. Study patterns of vegetation cover change in different environmental settings including different sides of the river and zones.

4. Determine the demography of Goodding willow through the river corridor of Grand Canyon and in the upper reach of Lake Mead, as a means of estimating the health of this population and its responses to river regulation.

STUDY AREA

The riparian plant community associated with the Colorado River in Grand Canyon National Park was studied. The river here has been regulated since the completion of Glen Canyon Dam in 1963. This dam was designed to provide flood control, hydroelectric power and water storage. Flooding (Fig. 1), sediment load and water temperature were all reduced following damming. Lake Powell, above the dam, was in the filling phase from 1963 to 1980. Low flows associated with this period were replaced by post-dam floods for several years after Lake Powell filled and above average snowpack occurred in the Rocky Mountains in 1983 and 1984. River flows in the mid- to late 1980's were characterized by daily fluctuations, generated in response to power demands. Daily fluctuations accelerated the rate at which beach sediments were eroding (BOR, 1995), and as a result, an 'interim flow' regime was established in 1990. Interim flows reduce the magnitude of daily fluctuations in flow that are released from Glen Canyon Dam, in an effort to reduce erosion rates.

Vegetation in three Glen Canyon Environmental Studies' (GCES) GIS reaches (8, 10, 13) in the lower Grand Canyon was studied (Fig. 2). Vegetation along the Colorado River is distributed in zones that relate to present and historical river flood levels, as well as vegetation types. The OHW zone of vegetation through the study sites is comprised predominantly of honey mesquite (*Prosopis glandulosa*) and catclaw acacia (*Acacia greggii*) in Reaches 8 and 10. These populations were thought to have been established during large, historical flooding events (Johnson 1991). There is no OHW zone vegetation in Reach 13. Reach 13 occurs where the Colorado River meets Lake Mead. The new high water (NHW) zone vegetation is directly riverside, extending up to the boundary of the OHW zone at an elevation that corresponds to 120,000 cfs pre-dam flooding. Native coyote willow (*Salix exigua*) and introduced tamarisk (*Tamarix ramosissima*) are dominant woody plants within the NHW zone in all three reaches. Goodding willow (*Salix gooddingii*) is common in GCES GIS Reach 13, and relatively rare throughout the rest of the Grand Canyon.

METHODS

GENERAL RIPARIAN VEGETATION PATTERNS: Aerial photography of Grand Canyon GCES GIS Reaches 8, 10 and 13 (Fig. 2) from five years (1965, 1973, 1984, 1990 and 1992; Table 1) was analyzed. Data from 1990 photographs were provided by the Bureau of Reclamation's (BOR) Remote Sensing Division in Denver, Colorado. Photography of Reach 13 from 1984 was unavailable; and 1973 photographs of this reach indicate that most vegetation was submerged due to high lake levels at Lake Mead, making them unusable.

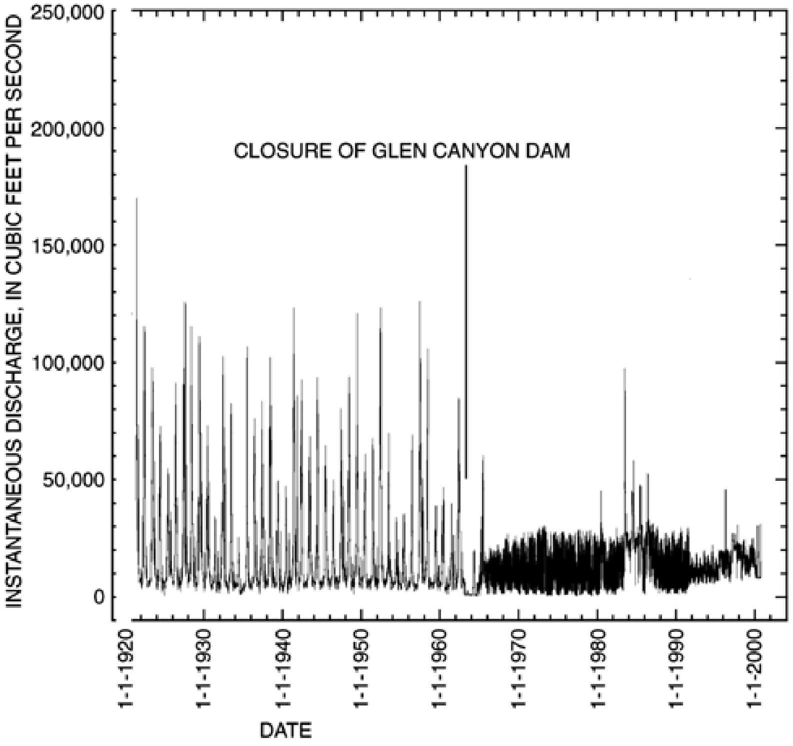


FIGURE 1. Minimum and maximum pre-and post-dam flow patterns of the Colorado River between 1940 and 2002 (Topping et al. 2002).

FIGURE 2. Location of GCES GIS Reaches in the Grand Canyon. Locations of Reaches 8, 10 and 13 are indicated on the map and in the box at upper left.

Table 1. Aerial photography used in this study.

YEAR	SCALE	FILM	DATE
1965	1:12,000	Black&White	5-14-65
1973	1:6,000	Black&White	6-16-73
1984	1:3,000	Black&White	10-22-84
1990	1:4,800	Colorinfrared	6-03-90
1992	1:4,800	Color	10-12-92

All photographs were developed to a 1:2,400 scale for ease of interpretation; this scale conforms with 1990 GIS base maps prepared for all Glen Canyon Environmental Studies (GCES) GIS reaches. Vegetation polygons were traced on high transparency mylar sheets overlying the photographs. Polygons were traced from vegetation lying only within the center one-third of each aerial photograph, to minimize distortion that occurs along the periphery of photographs. Two categories of vegetation were designated: NHW zone, OHW zone. Because some clumps of vegetation around which polygons were drawn contained gaps in coverage, the area of the polygons were adjusted by comparing the degree of canopy coverage per polygon with Forest Service vegetation cover density (=density of canopy cover) charts that were organized in the following categories: class 1 (0-20%), 2 (21-40%), 3 (41-60%), 4 (61-80%) or 5 (81-100%) These values were assigned to the polygons, following visual inspection of the aerial photographs and ground-truthing during two 10-day river trips. The mid-point within each vegetation class (i.e., class 1 mid-point = .10 or 10%) was multiplied by polygon area to produce an estimate of canopy cover density of polygons. These methods follow those of Wilson (1960).

Orthogonalized base maps at a scale of 1:2,400 were used in this study to provide georeference points for the mapping process. These maps were generated by the Bureau of Reclamation’s Remote Sensing Division from 1990 aerial photography of the Colorado River in Grand Canyon. By matching geographic features common to these rectified maps and our vegetation maps, we were able to avoid potential problems stemming from scale differences (between photograph sets), photodistortion and mosaicing.

Maps generated from 1992 aerial photographs were scaled and rectified with the use of a Zeiss © zoom transfer scope. This method served to correct distortions in the 1992 aerial photography, and provided accurate area and location information. These data were compared with 1990 vegetation data to understand vegetation change in response to interim flows, and to earlier photo sets to address patterns of historical change in vegetation cover. Maps generated from historical photographs dating from 1965, 1973 and 1984 were assigned approximately 25 reference points per river mile. The maps were then digitized into the GCES GIS, and given coordinate values established for the GCES GIS. The maps were 'rubber sheeted' into line with ortho base map points. The transformation and rubber sheeting processes provided some rectification of these data. This methodology provided area measurements of vegetation maps from these dates. Level of map accuracy was as follows: Maps from photographs dating from 1990 and 1992 conform with National Map Accuracy Standards of +/- 2 horizontal meters (Werth et al. 1993); maps from earlier than 1990 have an accuracy level of +/- 5 horizontal meters (Patrick Wright, 1996, personal communication).

Georeferenced maps were digitized by BOR's Remote Sensing Division in Denver, Colorado. The resulting data set included the following variables for each vegetation polygon: date; GIS reach; river mile; 1/10th mile section; side of river; vegetation category (the three aforementioned categories); area (m^2); and x and y coordinates. Vegetation data are presented in Appendix I.

Vegetation cover in m^2 per 1/10th mile was compared among years 1965, 1973, 1984, 1990 and 1992 to determine patterns of change from the initial phase of impoundment through post-dam flows and the initial phase of interim flows.

Environmental conditions, including side of the river and zone were analyzed.

These variables were analyzed to determine their effects on NHW vegetation cover.

GIS-derived data were transferred into an ASCII format, and then reformatted using Word for Windows 6.0 and Excel for Windows 6.0. Following this process, the data were analyzed using SYSTAT for Windows (Wilkinson 1991).

Because 1990 OHW vegetation cover was consistently lower than that in all other years, 1990 data were adjusted with the development of a correlation coefficient to bring them into line with the data sets that I created. By determining the relationship between BOR's interpretation of polygon area with mine, this methodology served to bring the 1990 data within range of data from other years, allowing for a more useful comparison of different data sets. This difference is due to different entities being involved in the mapping process: BOR mapped vegetation from 1990 aerial photographs, while I mapped vegetation from photographs from all other dates. With BOR in Denver, I developed a correlation coefficient between their estimate of vegetation cover in 1990 with my interpretation of 1990 vegetation cover. Vegetation was mapped by BOR and by me from 1990 photographs in three reaches, in the NHW and OHW zones. My measurements for 1990 polygons were correlated with those generated by BOR. The resulting correlation coefficient (38.077) was derived by correlating the two data sets. The 1990 data were adjusted as follows: Adjusted 1990 cover = 38.077 + 1.110 * (unadjusted 1990 cover)(Ullman 1978).

Multiple stepwise regression analyses were used to determine the extent of autocorrelation between adjacent 1/10th mile intervals of vegetation in each year in each reach in each zone on each side of the river. There was a significant correlation in vegetation cover between most adjacent 1\10th mile sections. Levels of autocorrelation in the data set for each reach were determined by conducting multiple stepwise regression of vegetated area with each of the next consecutive four 1/10th mile intervals. This analysis was done for each reach/year/side/zone combination, for a total of four zone/side analyses in each of five years, for a total of 20 multiple regression analyses in each reach (Appendix II). Autocorrelation effects were eliminated by removing autocorrelated 1/10th intervals.

The Friedman test, a nonparametric test, was used to address patterns of vegetation change among years in each reach. Vegetation change through time was analyzed with 1/10th mile intervals as blocks and years as repeated measures (Conover 1980). If OHW zone vegetation in Reach 8 on river left showed correlation between adjacent 1/10th miles, two data sets consisting of every other 1/10th mile were created and each was analyzed with a Friedman test. In several data sets there was correlation between vegetation cover in 1\10th mile intervals that were as much as 4-1/10th miles apart; in these cases, up to four subsets of data for each reach/side/zone combination were produced and up to four Friedman analyses were performed. The significance of all Friedman p values combined were evaluated with a serial Bonferroni test (Rice 1989). If individual Friedman tests were significant at $p < 0.05$, a Gibbons (1984) multiple comparisons test was used to determine which years were different. Percent change in vegetation cover was calculated by the following: Present cover - past cover\past cover* 100.

The Mann-Whitney test was used to assess differences in sides of the river on vegetation cover for each year (n=5)/ reach (n=3)/ zone (n=2) combination for a total of 30 tests. Test p values were subjected to a serial Bonferroni test (Rice 1989). A similar procedure was used to compare differences between NHW and OHW vegetation zones.

DEMOGRAPHY OF GOODDING WILLOW: Data collected on Goodding willow included the following: Cores for dendrochronology to measure age and growth patterns, and diameter at ground height. We originally intended to measure willows at breast height, but ultimately the use of diameter at ground height provided the best estimate of the size of the largest and main stem of Goodding willow, since the main trunk typically forked close to the ground, presumably at an early age. Dendrochronological information permitted the identification of relations between the demographics of this species and major high flow and low flow periods before and since river regulation.

Goodding willow populations were sampled at four sites: Lees Ferry in GCES GIS reach 2 (RM 0), in the Cardenas Creek area in GIS reach 5 (RM 70-72), and throughout most of GIS reach 13 (RM 273-276), where this species is particularly abundant. A population several hundred yards up Diamond Creek (RM 225 left) was sampled as a control population that was not influenced by river flows. Other individuals encountered through the river corridor were also cored and measured.

Dendrochronological information was collected from 290 Goodding willows (Appendix III), cored approximately 10 cm above the ground and diameters were measured at ground height (dgh). At each field site numbered tags were placed on cored willows, designating permanent references. These tags will help in long-term research on Goodding willow establishment and mortality along the Colorado River in Grand Canyon. Data are presented in Appendix III.

Following the procedures of Stokes and Smiley (1968), successively finer grades of sand paper revealed annual rings in mounted tree cores. Binocular microscopes enabled counting of tree rings, detection of periods of growth suppression and release, defined as a 250% change in mean ring width between consecutive groups of five rings, and determined initial growth. Initial growth rates compared preliminary growth to the rest of the tree's growth, classified as slow, medium or fast initial growth. This measure of initial growth helps in turn to determine if the tree started out under favorable conditions.

Long chronologies help to examine climatic, disturbance and river flow influences on tree growth. A computer-compatible incremental measuring machine assisted in determining ring widths (to the nearest 0.01 mm) on fifteen willows systematically selected in each of the four main sampling areas. In addition, subsequent visual cross-dating allowed for comparison with the computer cross-dating results.

The following programs helped in creating the tree-ring chronologies for each of the four sites. First, the tree-ring program COFECHA (Holmes 1983) assisted in locating missing rings or measurement errors in the tree-ring measurement series. Next, the program ARSTAN (Cook and Holmes 1992) created the tree-ring chronologies by detrending and indexing the measurement series, then creating a mean chronology. This study included both the cubic spline fit and the horizontal line fit. The cubic spline fit removes the ring-width variance attributed to tree growth geometry, whereby smaller rings are produced as trees age due to greater tree diameter, in order to detect the influence of climatic variation on ring width (Fritts 1976). In contrast, the horizontal fit does not remove the so-called biological growth trend, allowing detection of disturbance history (Veblen et al. 1991). By not removing age-related growth trend, the horizontal fit results typically show a declining line as the tree ages since rings become smaller with increased tree size.

RESULTS

GENERAL RIPARIAN VEGETATION PATTERNS:

Vegetation data in three GIS reaches for five separate dates between 1965 and 1992 are now entered into GCES' GIS. This constitutes a major contribution to the GIS, as all riparian vegetation in 10 miles from this study and 23 miles from the previous, related study (Waring 1996) are now accounted for within the GIS. Nearly half of the GCES Long-term Monitoring GIS sites are included.

Vegetation Change Through Time: 1965 to 1992

Pre-Dam Vegetation Along the Colorado River in Grand Canyon. Aerial photographs from 1965 revealed the presence of populations of both NHW and OHW zone vegetation (Table 2). In 1965, OHW vegetation covered 74,497 m^2 in the reaches studied. Most of these plants were in place prior to the completion of Glen Canyon Dam in 1963. NHW zone vegetation covered 873,504 m^2 in 1965, with most occurring in Reach 13 (Table 2).

Post-Dam Vegetation Riparian vegetation cover in both the NHW and OHW zones along the Colorado River in Grand Canyon increased 82% between 1965 and 1992. The area of vegetation cover in GIS reaches 8, 10 and 13 increased from 948,001.2 m^2 to 1,724,910.0 m^2 during this time period (Tables 2 and 3). This large change occurred despite post-dam flooding in the 1980's and indicates how productive riparian vegetation can be in a stabilized river system.

Nearly all post-dam increases in vegetation occurred in the NHW zone (Table 2, 3). NHW vegetation cover in GIS reaches 8, 10 and 13 increased from 873,504.6 m^2 to 1,641,718.0 m^2 (88%) between 1965 and 1992. NHW zone vegetation cover increases were significant in Reaches 8, 10 and 13 (Table 3).

As with upstream reaches from an earlier, related study (Reaches 2, 4 and 5, Waring 1996), NHW vegetation cover decreased by 17% in Reach 8 between 1973 and 1984, with post-dam flooding, although this trend was not significant (Table 3). Plant cover increased during the same time frame in Reach 10. Perhaps the scouring effects of post-dam flooding are mitigated downstream from the dam.

Flow levels following post-dam flooding in the early 1980's were stable and low (Fig. 1), resulting in the largest increases in vegetation. NHW vegetation cover in Reaches 8 and 10 increased by more than 183% between 1984 and 1992 (Table 2). NHW vegetation increased by 131% between 1965 and 1984. Because post-dam flooding occurred into 1986, vegetation cover probably did not increase substantially until after that period. These data suggest that a large part of post-flood vegetation gain occurred during the interim flow period.

NHW vegetation cover increased significantly between 1990 and 1992 in Reaches 8 and 13, and decreased in Reach 10 between these years (Table 2, 3). The latter pattern may be attributable to methodology rather than real change (Table 2, see Methods).

Table 2. Vegetation cover in square meters, in GCES GIS Reaches 8, 10 and 13, 1965-1992.

VEGETATION COVER AREA:				**YEAR:**	
REACH 8	**1965**	**1973**	**1984**	**1990**	**1992**
OHW:	13,605.9	13,376.4	15,421.7	21,181.3	18,662.3
NHW:	3,628.2	11,003.5	9,143.7	18,220.0	31,164.7
TOTAL:	17,234.1	24,379.9	24,565.4	39,401.3	49,826.9
REACH 10					
OHW:	60,891.1	48,223.4	64,858.5	64,601.1	64,529.8
NHW:	6,360.2	9,959.2	13,908.8	41,990.2	34,234.8
TOTAL:	67,251.3	58,182.6	78,767.3	109,028.3	98,764.6
REACH 13					
OHW:	0.0	0.0	----	83,264.2	0.0
NHW:	863,516.6	----	----	1,352,282.5	1,576,317.9
TOTAL:	863,516.6	0.0	----	1,435,546.7	1,576,317.9

Table 3. Analysis of NHW and OHW vegetation coverage through time. Data organized by reach, zone, and side of the river*. Friedman tests, using Gibbon's multiple comparison test and serial Bonferroni adjusted probabilities are reported. Different letters by Friedman values indicate significant differences between years.

n	REACH	ZONE	SIDE	FRIEDMAN	P	1965	1973	1984	1990	1992	GIBBONS CRITICAL VALUE (p<.05)
51	8	NHW	L	86.68	0.000	94.0a	138.0b	125.0b	179.5c	229.5d	30.03
51	8	NHW	R	96.98	0.000	89.5a	151.0b	126.0b	158.5bc	240.0d	28.72
52	8	OHW	L	9.05	0.060	146.5	145.0	143.5	161.0	184.0	39.87
52	8	OHW	R	2.17	0.700	150.5	163.5	160.0	144.0	162.0	35.46
25	10	NHW	L	48.22	0.000	41.5a	63.5ab	67.5b	88.5c	114.0d	21.68
26	10	NHW	R	42.12	0.000	56.0a	61.0a	64.0ab	91.0b	118.0c	24.87
26	10	OHW	L	19.10	0.000	81.5b	49.0a	90.0b	76.0b	93.5b	28.81
14	10	OHW	R	9.48	0.060	41.0	42.0	31.0	36.0	45.0	25.48
13	10	OHW	R	10.55	0.050	23.0a	43.0ab	33.0a	51.0b	45.0ab	19.87
33	13	NHW	L	52.06	0.000	51.0a	--	--	85.0b	97.0c	7.06
33	13	NHW	R	42.61	0.000	37.0a	--	--	72.0b	89.0c	9.10

* n: number of 1/10th mile samples; side: L = left side of river, R = right side of river.

OHW vegetation cover increased by 37% between 1965 and 1992 in Reach 8. This pattern was not significant (Table 3). In Reach 10 this vegetation zone covered a smaller area in 1973 than any other year (Tables 2 and 3). There was no OHW vegetation in Reach 13 although area for this zone is listed in the 1990 BOR data set.

Vegetation Change and Other Environmental Effects

Reaches and Vegetation Zones. Patterns of riparian plant distribution in the NHW and OHW zones differed among Reaches 8, 10 and 13. In general, area of NHW zone vegetation cover was initially less than that of OHW in 1965 in Reaches 8 and 10, but expanded and exceeded OHW area by 1992 (Table 4). This was not the case on river right in reach 10, where OHW vegetation continued to cover a larger area than NHW vegetation through all years, due to limited colonizable substrate in the NHW zone (Tables 4 and 5).

The greatest percent increase in NHW plant cover occurred in Reach 8 (189%) between 1965 and 1992 and least in Reach 10 (49%) during this time.

Distance Downstream Effects on Vegetation Cover. Amount of increase in NHW plant cover in Reaches 8, 10 and 13 and those upstream (Reaches 2, 4 and 5, from Waring 1996) between 1965 and 1992 suggests that the greatest increases have occurred within the canyon interior rather than at its beginning and end (e.g., Lees Ferry and Reach 13; Table 6). Perhaps since sediment deposits got so large in Reach 13, more sediment has been trapped further upstream, resulting in a greater percent expansion of colonizable beach habitat there.

Side of the River and Vegetation Distribution. Significantly more OHW zone vegetation occurred on the left, north-facing side of the river in reach 8. This difference was significant in nearly all years measured (Tables 4 and 5). This was the only significant difference in vegetation cover on different sides of the river.

Table 4. Mean (top), standard deviation (below), and number of tenth mile sections of vegetation cover (in square meters) in three reaches of the Colorado River by side of the river (left and right) and vegetation zone (NHWand OHW) from 1965 to 1992.

REACH	SIDE	ZONE	1965	1973	1984	1990	1992	n
8	LEFT	NHW	29.1	76.6	65.4	140.3	232.9	55
			51.35	118.43	114.30	191.04	278.49	
8	RIGHT	NHW	42.1	123.5	100.8	166.0	333.7	55
			92.23	218.26	249.75	302.78	516.41	
8	LEFT	OHW	156.0	144.1	162.6	178.8	219.6	55
			212.29	174.77	228.80	203.11	288.80	
8	RIGHT	OHW	105.6	99.1	117.8	97.6	119.7	55
			193.08	159.28	218.44	180.66	217.56	
10	LEFT	NHW	141.2	227.1	364.3	1,236.4	792.3	27
			196.65	204.23	348.23	2,811.14	597.54	
10	RIGHT	NHW	108.8	141.7	150.9	318.8	475.7	27
			108.62	152.65	181.73	374.73	377.32	
10	LEFT	OHW	979.9	556.7	1,079.4	1,064.9	1,025.4	27
			806.12	501.42	939.68	868.50	882.42	
10	RIGHT	OHW	1,362.0	1,229.6	1,322.8	1,327.7	1,364.5	27
			1,987.7	1,385.6	1,979.8	1,162.7	1,713.1	
13	LEFT	NHW	11,115.9	----	----	19,953.7	21,791.5	33
			8,265.2			12,939.3	13,906.0	
13	RIGHT	NHW	15,051.3	----	----	23,427.8	25,975.7	33
			18,089.6			25,647.0	25,958.1	

TABLE 5. Vegetation zone tests. Mann Whitney test, p (in parentheses) and serial Bonferroni adjusted significance levels (indicated by *), for comparisons of vegetation cover on both sides of the river within reaches, zones and years.

REACH	SIDE	1965	1973	1984	1990	1992
8	L	681.01* (.000) n=103	1,157.5 (.031) n=110	1,198.0 (.053) n=110	1,335.0 (.283) n=110	1,642.0 (.435) n=110
8	R	1,176.0 (.285) n=103	1,697.0 (.262) n=110	1,662.0 (.352) n=110	1,843.0 (.037) n=110	2,320.0* (.000) n=110
10	L	104.0* (.000) n=51	216.0 (.010) n=54	191.0 (.002) n=54	239.0 (.029) n=54	309.5 (.340) n=54
10	R	74.0* (.000) n=52	70.0* (.000) n=54	94.0* (.000) n=54	152.0* (.000) n=54	203.0* (.005) n=54

TABLE 5 (cont.) Side of River Tests. Mann Whitney test, p (in parentheses) and serial Bonferroni adjusted significance levels (indicated by *), for comparisons of vegetation cover on both sides of the river within reaches, zones and years.

REACH	ZONE	1965	1973	1984	1990	1992
8	NHW	.078 (.779) n=103	1.473 (.225) n=110	2.200 (.138) n=110	.073 (.787) n=110	1.472 (.225) n=110
8	OHW	8.481* (.004) n=103	4.655* (.031) n=110	3.073 (.055) n=110	11.364* (.000) n=110	4.655* (.031) n=110
10	NHW	.040 (.841) n=51	2.370 (.124) n=54	1.815 (.178) n=54	2.370 (.124) n=54	1.815 (.178) n=54
10	OHW	1.385 (.053) n=52	3.000 (.083) n=54	3.704 (.054) n=54	1.333 (.248) n=54	0.000 (1.000) n=54
13	NHW	0.030 (.862) n=56	----	----	0.272 (.602) n=55	0.030 (.862) n=54

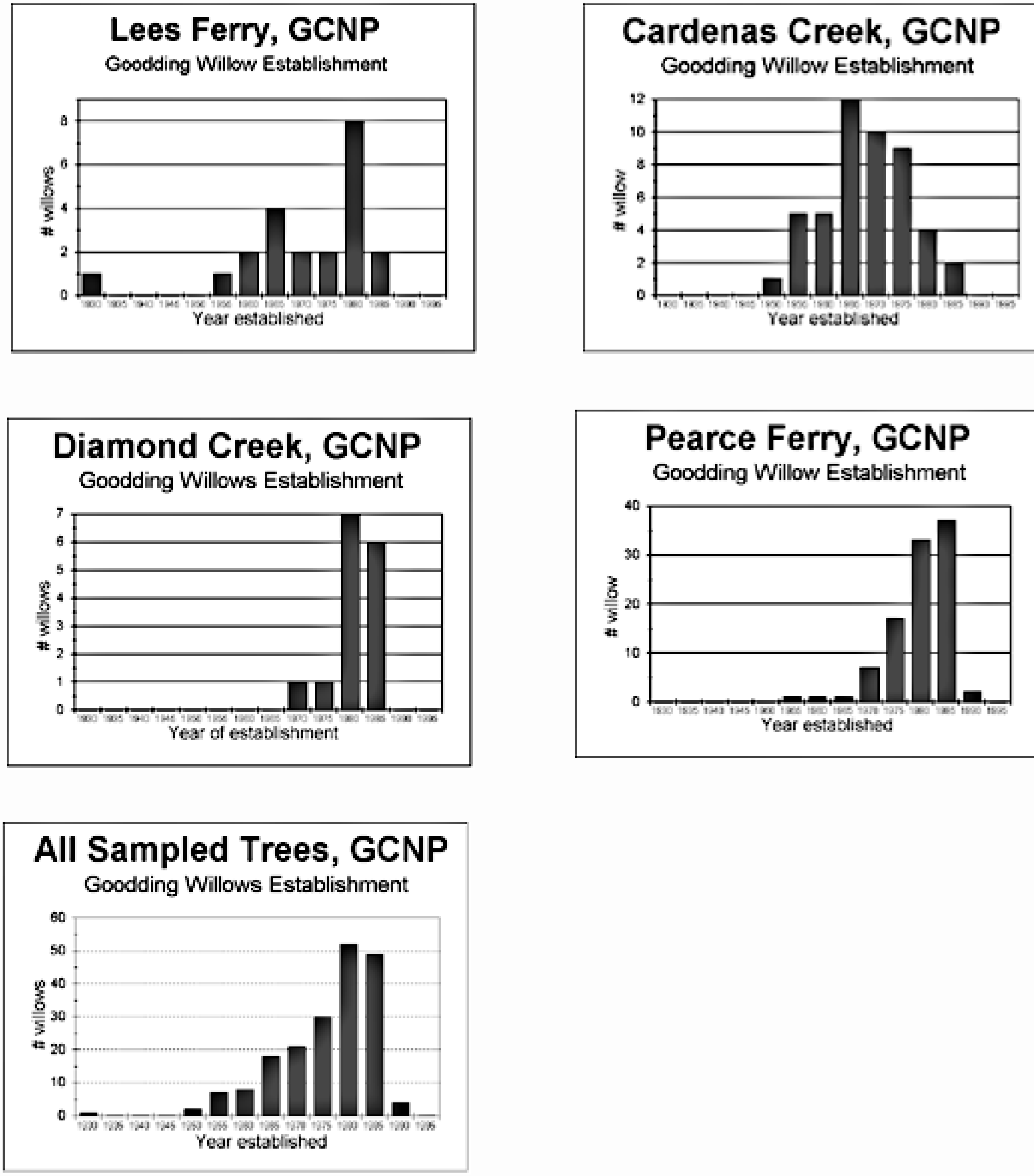
Table 6. Percent increase in NHW zone plant cover between 1965 and 1992, in GCES GIS Reaches 2, 4, 5, 8, 10, and 13. Data for Reaches 2-5 from Waring (1996).

REACH	PERCENT COVER INCREASE FROM 1965-1992
2	72%
4	148%
5	197%
8	759%
10	438%
13	82%

DEMOGRAPHY OF GOODDING WILLOW:

Age Analyses. Overall, 77% of the 290 Goodding willows cored possessed piths (23% with minimum age due to rotten centers). The percentage of cores with a complete pith age varied strongly by site: 28% at Lees Ferry, 83% at Cardenas Creek, and 98% in Reach 13. Overall, the age structure of populations for all sites indicated that the majority of trees were young, having become established since the closing of Glen Canyon Dam in 1963 (Fig. 3). It important to note, however, that the largest Goodding willows provided only minimum ages, due to rotten centers; hence, they are not represented in the age structure diagrams.

The site farthest upstream, Lees Ferry, contains the oldest measured willows, which date back to the 1930's (Fig. 3). Of the 80 willows sampled at Lees Ferry (nearly all plants were sampled there), 65% of the Goodding willows were multistemmed, 38%



Lees Ferry, GCNP

Goodding Willow Establishment

Cardenas Creek, GCNP

Goodding Willow Establishment

Diamond Creek, GCNP

Goodding Willows Establishment

Pearce Ferry, GCNP

Goodding Willow Establishment

All Sampled Trees, GCNP

Goodding Willows Establishment

Figure 3. Goodding willow establishment patterns at Lees Ferry, Cardenas Creek, Reach 13 and Diamond Creek. Dates are based on dendrochronological analysis of cores from willows at these sites.

possessed one or more dead stem, and 12% of the trees were dead (Table 7). The majority of willows at this site could not be aged due to rotten centers (72%) or tree mortality. Of willows aged to the pith at this site, 64% were established either between 1968-1973 (post-dam establishment) or between 1983-1986 (post-1983 flood establishment).

At the second site, Cardenas Creek, two Goodding willows date back to 1958 (Table 7). Of the 60 Goodding willows sampled, 50% were multistemmed, 22% had at least one dead stem, and no plants were dead. Only 17% of trees had rotten piths, enabling a better estimate of population age than at Lees Ferry. More than 50% of trees aged at Cardenas Creek were established between 1963-1964 and 1966 and 1968, as well as 1974-1976 (after an increase in maximum flow in 1973).

At the downstream site of GIS Reach 13, one willow was established in 1957 (Table 7), while the remaining plants were established after 1972 (total n = 110). Sixteen percent were multistemmed, and none were dead or had dead stems. Nearly all willows were aged to the pith here (98%). In Reach 13, 58% of the willows aged were established during and following post-dam flooding. This period coincides with some of the highest lake levels for Lake Mead recorded within the last 30 years (Fig. 4).

At Diamond Creek, the control site for this study, willows dated back only to 1972, although 2 large trees could not be aged (Fig. 3, Table 7). Of the 20 willows sampled, 40% had multiple stems, none of which was dead. Only 25% of the trees had rotten piths. Forty percent of trees here were established in 1981, 1982 or 1986.

<u>Growth Analyses</u>. Comparing sites along the Colorado River, results from master chronologies showed impacts of the damming of the river through growth suppressions (Fig. 5). At Lees Ferry, significant growth suppression occurred starting in 1964, a year after dam completion (Fig. 5). In contrast, Goodding willows farther downstream at Cardenas Creek showed suppression starting in 1970, seven years after the dam was completed. Delayed reactions may be due to mitigating effects of the Little Colorado River, whose confluence occurs nine miles upstream of Cardenas Creek. Similarly, Goodding willows measured in Reach 13 displayed a marked suppression starting in 1971. This may be due to an increasing lake elevation at Lake Mead (Fig. 4).

Comparing sites along the Colorado River, Cardenas Creek's master chronology showed a significant increase in growth after post-dam flooding in the early 1980's (Fig. 5). These willows showed a clear growth increase starting in 1985, possibly resulting from post-dam flooding. By contrast, both Lees Ferry and Reach 13 showed increased growth only after 1990. Increased growth of Goodding willows in Reach 13 may have been stimulated by dropping lake elevations at Lake Mead (Fig. 4).

Diamond Creek showed potentially climate-induced growth trends. Periods of suppression of growth there occurred during 1976-1977 and 1980-1982, with periods of release occurring in 1975 and 1978. None of the river sites displayed significant suppression or release during these same periods. The Diamond Creek master chronology displayed no evidence of release associated with post-dam flooding during the early 1980's, an anticipated result since Colorado River flow fluctuations were not expected to influence these willows (Fig. 5).

Table 7. Demographic features of Goodding willow sampled at Lees Ferry, Cardenas Creek, Reach 13 and Diamond. Parameters include % trees sampled containing a pith, % multistemmed trees, % dead trees and earliest measured date of establishment.

SITE	% PITH	% MULTISTEMMED	% MORTALITY	EARLIEST ESTABLISHMENT
Lees Ferry	28%	65%	12%	1930
Cardenas Ck.	83%	50%	0	1958
Reach 13	98%	16%	0	1957
Diamond Ck.	75%	40%	0	1972

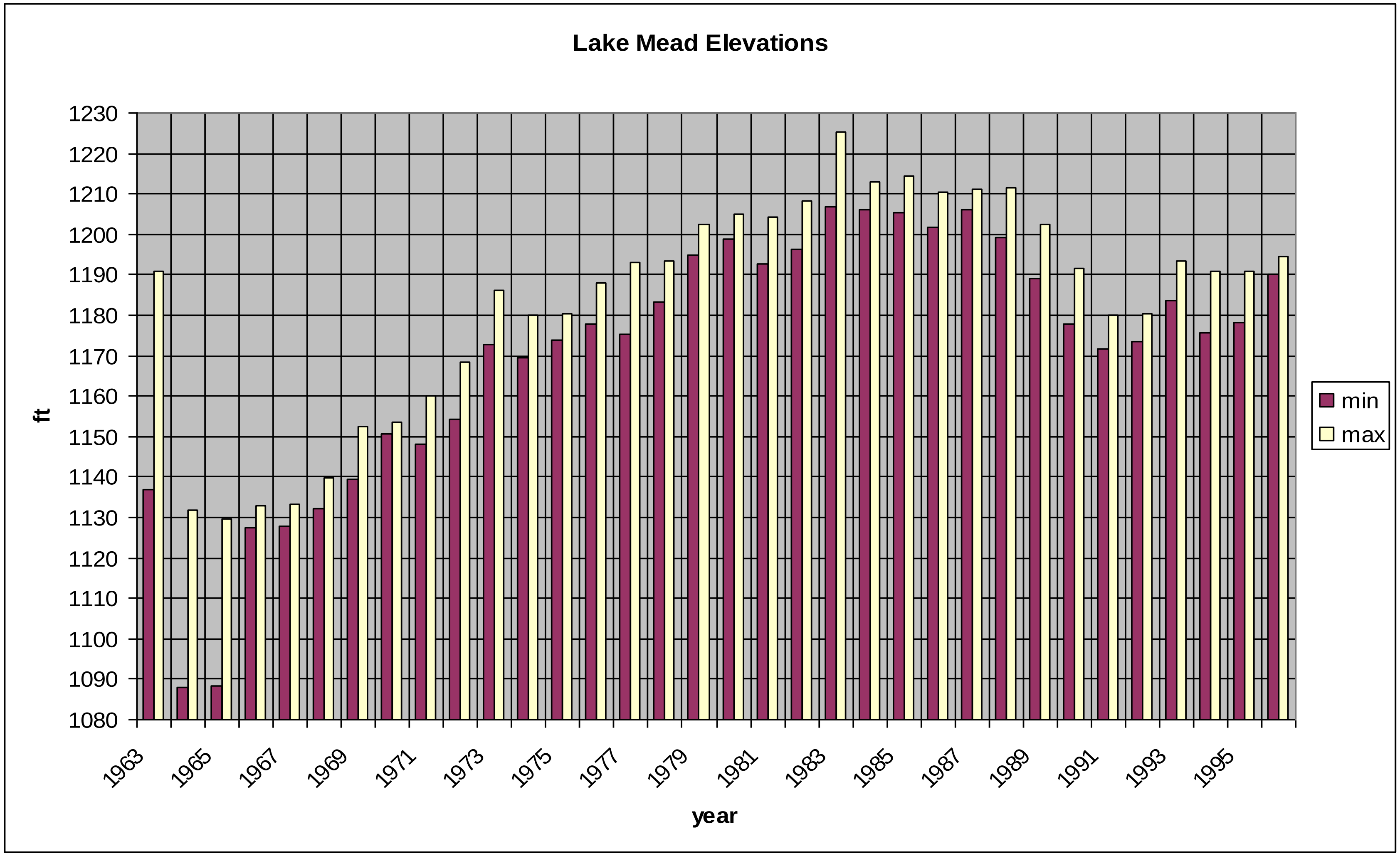


Figure 4. Minimum and maximum elevations (in feet) of Lake Mead between 1963 and 1995. (BOR Lower Colorado River Region, Boulder City, Nevada, 1996).

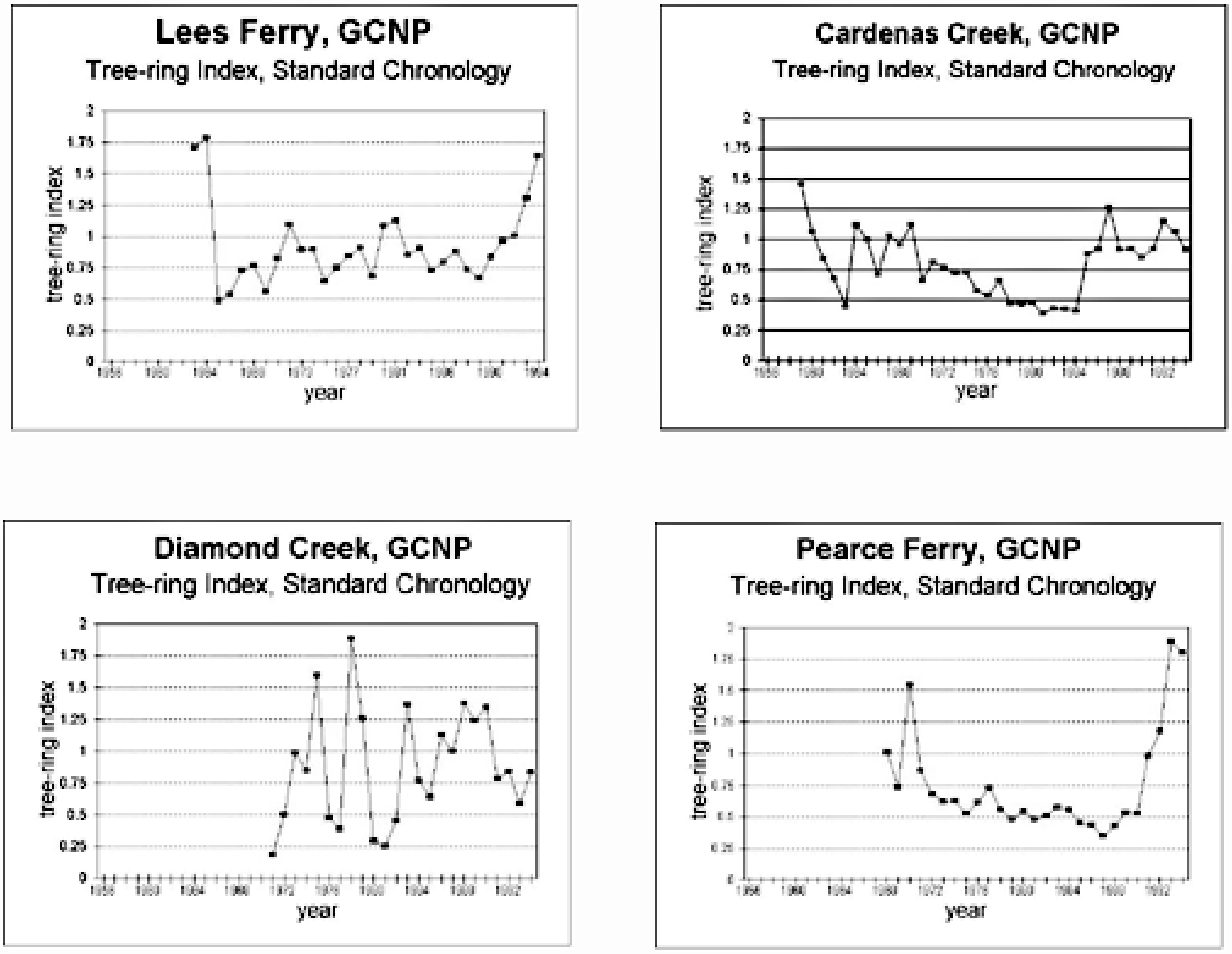


Figure 5. Goodding willow growth chronologies, based on tree ring analyses of plants from Lees Ferry, Cardenas Creek, Reach 13 and the control site, Diamond Creek. Larger values on the charts reflect periods of increased growth.

Size Analyses. size analyses for cored willows (based on diameters at ground height) at the four sites followed a typical reverse-J curve, with the majority of trees in the smaller (5-20 cm dgh) size classes (Fig. 6). When analyzed by site, Lees Ferry possessed the most large diameter willows, with seven trees (9%) at 57-87 cm dgh. Two other cohorts exist for Goodding willows at Lees Ferry: 39 trees (49%) at 10-25 cm dgh and 14 trees (18%) at 30-49 cm dgh. One Goodding willow at Cardenas Creek reached 85 cm dgh, but the majority (78%) ranged from 10-25 cm dgh. By contrast, the largest Goodding willow sampled in Reach 13 attained only a 33.5 cm dgh, with almost all Goodding willows sampled there (91%) being between 5-20 cm dgh. Similarly, at the control site of Diamond Creek, almost all Goodding willows achieved a diameter at ground height of less than 20 cm, with only one large tree at 55 cm dgh.

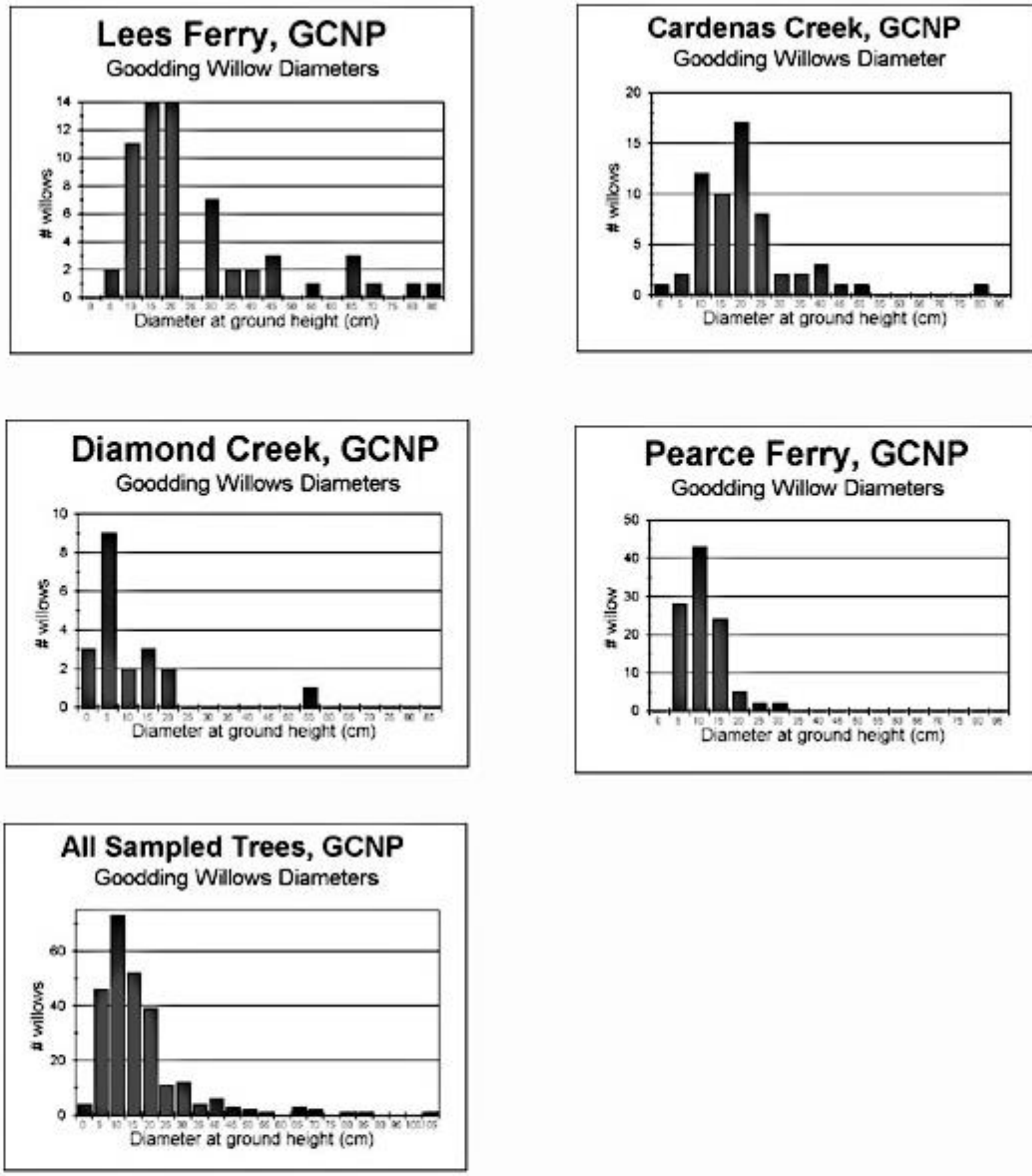


Figure 6. Size classes of Goodding willow at different Grand Canyon sites.

Miscellaneous Sites. Twenty additional willows were measured and cored as encountered through the river corridor. Nine (45%) of these could be aged. The oldest plant, found at Unkar Rapids (RM 72.5 right), was established in 1953. All other plants were established in the post-dam period. Fifty-five percent of the aged plants were established between 1986 and 1991.

The largest plant, at Granite Park (RM 209 left), had a dgh of 109 cm (this is a conservative diameter estimate due to construction around the base of this plant). Although undatable due to a rotten pith, this plant is represented in one of the Robert Stanton photographs taken approximately 100 years ago (Webb 1996).

DISCUSSION

This study of large-scale and species-specific plant responses to river regulation finds that NHW riparian vegetation in general and flood-dependent Goodding willow, in particular, are thriving within this dammed river system. Following previous work within this system (Waring 1996), the dramatic increase of NHW riparian vegetation cover in the lower Grand Canyon between 1965 and 1992 was expected; however, the establishment success of Goodding willow within this system was a welcome surprise. Few studies have reported successful establishment of flood-dependent tree species in regulated-river systems (Waring 1993).

Because more than 60% of the Goodding willow measured at Lees Ferry and Pearce Ferry became established following the post-dam flooding event of the early 1980's, it appears that this flood-dependent species can establish itself even within the context of a modified, post-dam flood. Despite the fact that the quality of riparian soils relative to plant establishment and growth has been declining since post-dam flooding (Stevens and Waring 1988), these substrates appear adequate to support Goodding willow. It is likely that the establishment of the enormous population of Goodding willow in lower Grand Canyon (Reach 13) is tied to the quality of sediment there, where sediment appear fine-grained and particularly muddy (Waring, personal observation).

There are several ways in which riparian vegetation is persisting in this dam-regulated system: by becoming established throughout the canyon following post-dam flooding, by 'following' sediment downstream and/or by colonizing sediment benches that develop where this river meets Lake Mead. The latter is where all riparian vegetation in this system, along with Goodding willow, has become most abundant. An enormous NHW zone riparian plant population was already in place by 1965 in Reach 13, which lies at the top of Lake Mead; this being due to a large accumulation of fine-grained sediment from the Grand Canyon that drop out of the Colorado River as it reaches the still waters of the lake.

This study combined with the previous work (Waring 1996) offered the opportunity to consider vegetation patterns with increasing distance downstream. The largest increases in vegetation occurred within the canyon rather than at its beginning or end, suggesting that perhaps the rate of sediment deposition may be greatest in this region. While it was not surprising that increase in plant cover was least at Lees Ferry due to a lack of tributary input, it was surprising that the percent of expansion of vegetation cover in Reach 13 was also lower than at other points in the Canyon. One possible cause may be that sediments are starting to accumulate upstream of this reach following long-term sediment deposition in Reach 13.

Post-dam flooding effects on vegetation also varied with distance downstream from Glen Canyon Dam. Post-dam flooding did not result in the magnitude of loss of vegetation cover in the lower GIS reaches that it did in the upper Grand Canyon. Of the two lower reaches measured, there was an estimated 17% loss of cover in Reach 8, while vegetation cover increased during this period in Reach 10. These patterns suggest that there may be a reduction in scouring flooding effects further downstream.

This study demonstrated that the regulation of the Colorado River through Grand Canyon directly resulted in the creation of an extensive riparian plant community.

MANAGEMENT RECOMMENDATIONS:

Riparian vegetation in more than 33 miles (>50% of river miles) of long-term monitoring GIS sites along the Colorado River are now accounted for within the GCES GIS. These vegetation data in six GIS reaches and five separate dates between 1965 and 1992 exist as a permanent record that can be accessed for future reference and comparisons. This constitutes a valuable tool for the National Park Service and other entities that may conduct research on riparian vegetation and its relationship to other elements of the river ecosystem.

This study found that riparian vegetation has increased with impoundment and that increases were greatest during periods stable, lower flows. The greatest increases in vegetation occurred in the middle portion of the Grand Canyon; this trend is worthy of further study, particularly to determine the relationship with sediment deposition trends.

The future success of Goodding willow in the Grand Canyon deserves additional study. While an enormous population occurs in Reach 13, that site may offer a precarious future for riparian vegetation due to fluctuating lake levels. It would also be worthwhile to measure growth responses to the spike flow of 1996.

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ABSTRACT

A series of aerial photographs of eight river miles in three reaches of the Colorado River in Grand Canyon was analyzed to determine the response of associated riparian vegetation to river regulation. Vegetation maps were drawn from photograph sets dating from 1965, 1973, 1984, 1990 and 1992 and entered into Glen Canyon Environmental Studies Geographic Information Systems (GCES GIS). The demographics of one species, *Salix gooddingii*, were studied in detail, including a dendrochronological analysis.

Riparian vegetation cover in the New High Water zone (NHW), or along the active channel margin, in GCES' GIS Reaches 8, 10 and 13 in Grand Canyon National Park increased more than 88% between 1965 and 1992. This occurred despite a post-dam flooding period in the early 1980's that reduced vegetation cover and illustrates how productive riparian vegetation can be in a stable setting such as that created by a regulated river. Following the post-dam flooding event in the early 1980's, NHW riparian vegetation cover again increased at a rapid rate, with the result that cover was greatest by the final date measured in 1992. Vegetation cover in the Old High Water zone (OHW) increased slightly between 1965 and 1992.

A demographic study of Goodding willow (*Salix gooddingii*)-a tree willow in Grand Canyon-has determined that more than 50% of these trees were established after the closing of Glen Canyon Dam in 1963. The oldest tree cored (with a pith present) was established in 1930 at Lees Ferry; however, a tree at Granite Park at river mile 209 dates back to the 1800's, according to a photograph taken of this tree by Stanton in 1890. The youngest and largest population of Goodding willow occurs at the western end of Grand Canyon where the Colorado River meets Lake Mead.

Establishing a quantitative historical perspective of vegetation change in GIS reaches was a primary aim of this research. With this study and previous work, historical vegetation data are available for nearly half of GCES' GIS reaches. It provides an important reference point for all future research on riparian vegetation in Grand Canyon.

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