

## DAM IMPACTS ON AND RESTORATION OF AN ALLUVIAL RIVER – RIO GRANDE, NEW MEXICO

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### ABSTRACT

The impact of construction of dams and reservoirs on alluvial rivers extends both upstream and downstream of the dam. Downstream of dams, both the water and sediment supplies can be altered leading to adjustments in the river channel geometry and ensuing changes in riparian and aquatic habitats. The wealth of pre and post-regulation data on the Middle Rio Grande, New Mexico, provides an excellent case study of river regulation, channel adjustments, and restoration efforts. Cochiti Dam was constructed on the main stem of the Rio Grande in 1973 for flood control and sediment retention. Prior to dam construction, the Rio Grande was a wide, sandy braided river. Following dam construction, the downstream channel bed degraded and coarsened to gravel size, and the planform shifted to a more meandering pattern. Ecological implications of the geomorphic changes include detachment of the river from the floodplain, reduced recruitment of riparian cottonwoods, encroachment of non-native saltcedar and Russian olive into the floodplain, and degraded aquatic habitat for the Rio Grande silvery minnow. Recent restoration strategies include removal of non-native riparian vegetation, mechanical lowering of floodplain areas, and channel widening.

**Key Words:** River morphology, Effects of dams, Rio Grande

### 1 INTRODUCTION

The construction of more than 75,000 dams and reservoirs on rivers in the United States (Graf, 1999) has resulted in alteration of the hydrology, geometry, and sediment flow in many of the river channels downstream of dams. Additionally, hydrologic and geomorphic impacts lead to changes in the physical habitat affecting both the flora and fauna of the riparian and aquatic environments. Legislation for protection of endangered species as well as heightened interest in maintaining more natural river corridors has prompted numerous studies of both the historic natural state and the altered post-regulation state to determine successful management and restoration strategies. The Middle Rio Grande in New Mexico is a regulated river caught between the conflicting goals of maintaining a safe river corridor, supporting native fish and bird species, and providing water for agricultural, municipal, and industrial uses (Richard, 2001).

Downstream geomorphic and ecological impacts of dams vary with the operational strategies of dams and with the characteristics of downstream river channels. Studies of regulated rivers have revealed varying responses including narrowing, widening, degradation, and aggradation occurring at different temporal scales (e.g., Xu, 1996, 1997). For example, Friedman et al. (1998) found from a study of 35 dams on large rivers in the Western U.S. that rivers with braided patterns tended to narrow following dam construction, and that meandering rivers experienced reduction in the channel migration rate.

Given the complexity of ecological and geomorphic response of rivers to dam and reservoir construction, case studies of rivers for which both pre and post-dam data are available are valuable. Understanding the river's dynamics prior to dam construction can enhance our understanding of the impacts of a dam on the downstream river reach. Quantifying the historical water and sediment inputs to a river reach and identifying the resulting responses can aid in understanding the changes induced by dam construction.

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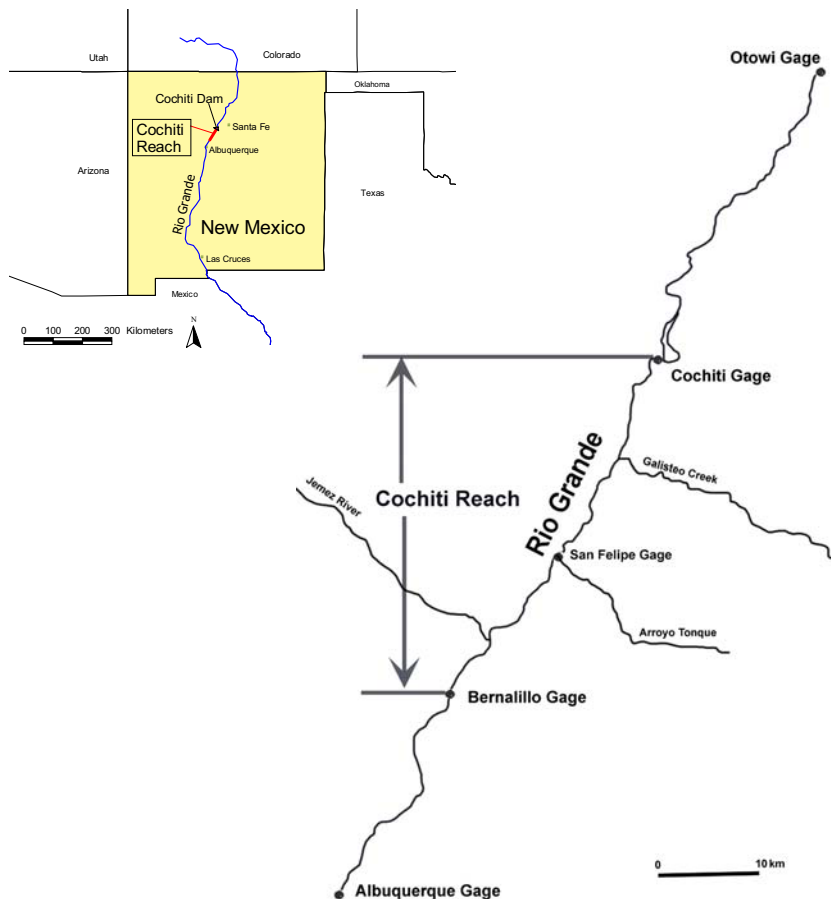
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Note: Discussion open until June 2004.

Using data collected on the Cochiti reach of the middle Rio Grande between 1918 and 2001, this paper presents a case study of river regulation, channel adjustments, and restoration efforts. The active adjustment of the Cochiti reach resulting from natural and anthropogenically induced variation in water and sediment discharge combined with the documentation of these changes over the last 100 years by state and federal agencies provide an excellent opportunity to explore the relations between changes in channel processes and the resulting channel form. Changes in the water and sediment inputs are described, followed by a discussion of the ensuing channel adjustments. The resulting ecological implications and restoration efforts are also described.

## 2 SITE BACKGROUND - MIDDLE RIO GRANDE

The Cochiti reach of the Rio Grande, located in north central New Mexico, extends 45 km downstream from Cochiti Dam (Fig. 1) to the Highway 44 Bridge in Bernalillo, NM. The Middle Rio Grande, of which the Cochiti reach is a part, has a long history of regulation, diversion, and anthropogenic activities beginning with the Pueblo Indians diverting water from the Rio Grande centuries ago. Major regulation of the river began in the 1920's with the construction of numerous diversion structures, dams, levees, and channelization works. Later, in the mid-1900's the construction of levees to prevent avulsions into surrounding agricultural land along the river exacerbated the previous aggradational trend by confining sediment deposition to a smaller area (Scurlock, 1998).



**Fig. 1** Location map Cochiti Reach, Rio Grande, New Mexico. Locations of major tributaries and U.S. Geological Survey (USGS) gaging stations are indicated

Cochiti Dam was completed in November 1973 for the purposes of flood control and sediment detention (U.S. Army Corps of Engineers, 1978). Located 65 km upstream of the City of Albuquerque,

Cochiti Dam controls a drainage area of about 37,800 km<sup>2</sup> (Bullard and Lane, 1993). Construction of the dam has resulted in significant impacts on the channel downstream including degradation of the channel bed and coarsening of the bed from sand to gravel size (Richard, 2001; Leon, 1998; Lagasse, 1994).

Data collection began on the Rio Grande in 1889 with the establishment of the first gaging station in the United States at Embudo, New Mexico. The combination of severe flooding and sedimentation along with irrigation needs in the middle Rio Grande valley in the early 1900's prompted continued data collection. Cross section surveys were collected beginning in 1918, bed material sampling began in the 1930's, suspended sediment measurements were initiated in the 1940's, and aerial photography or topographic surveys are available from 1918 to 2001. The net result of these data collection efforts is comprehensive documentation of the Cochiti reach for almost 100 years.

### 3 HYDROLOGIC REGIME AND SEDIMENT SUPPLY

Stream gage data along the Cochiti reach are available from 1895 to 1997 at several U.S. Geological Survey (USGS) gaging stations with the earliest record beginning in 1895 at the Otowi station (Leon et al., 1999). The water-discharge data were collected by the USGS and recorded as daily mean discharge measurements. Locations of the gaging stations are indicated in Fig. 1. The Otowi gage, located upstream from Cochiti reservoir, is used as the non-regulated reference discharge for the post-dam period. No major tributaries enter the Rio Grande between the Otowi gage and Cochiti reservoir. The Cochiti gage is located just downstream from Cochiti Dam and began operation in 1927. Further downstream are the San Felipe gage (1927-present), the Bernalillo gage (1929-1969) and the Albuquerque gage (1942-1997). The two largest tributaries, Galisteo Creek and the Jemez River, are also gauged.

Spring snowmelt peaks occurred in most years with smaller peaks occurring during the late summer from thunderstorms. The time series of annual peak flows at the Otowi and Cochiti gages combined (that is, the Otowi gage used from 1895-1926 and the Cochiti gage used from 1927-1996, statistical tests were done to ensure that Otowi gage is representative of pre-dam flows at the Cochiti site) are presented in Fig. 2 from 1918 to 2001.

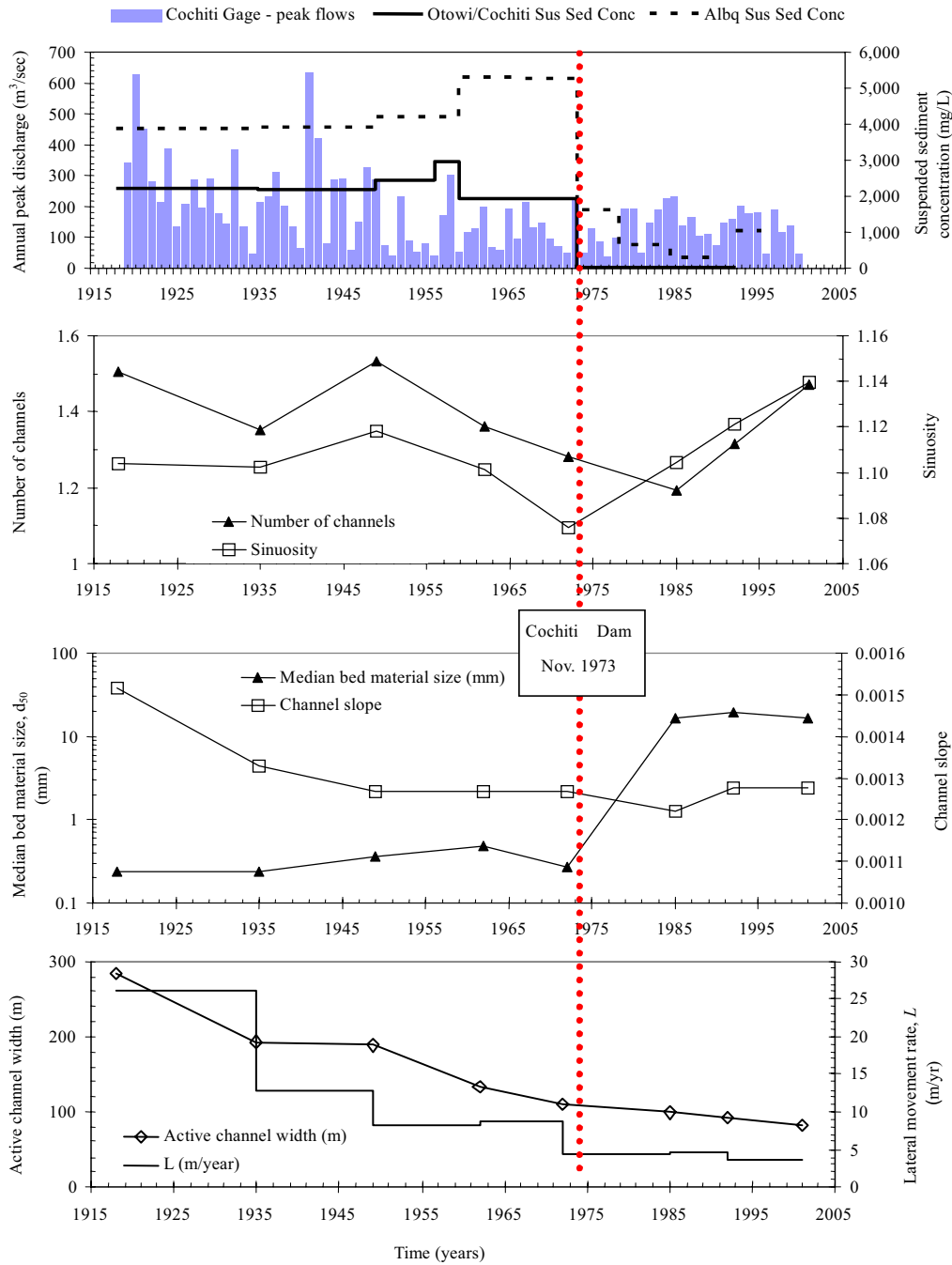
Statistical procedures (Richter et al., 1996) were used to compare the water discharge records prior to and following dam closure at the Otowi, Otowi/Cochiti combined, and Albuquerque gages. The mean daily discharge records were grouped according to water year and divided between pre-dam (prior to 1974) and post-dam (1974-1995) periods for the un-regulated flow (Otowi gage), the inflow to the study reach downstream of Cochiti dam (Cochiti gage), and the outflow from the study reach (Bernalillo/Albuquerque gages). The results of comparing the mean values of the one-day maximum flow, the mean annual flow and the duration of the high flows (106, 99, and 68 m<sup>3</sup>/s at Otowi, Otowi/Cochiti combined, and Albuquerque, respectively) for the pre and post dam periods are presented in Table 1. The one-day maximum (annual flood) decreased at all of the gages, with the greatest decrease being just downstream of the dam at the Cochiti gage (38%). The duration of the high pulse as well as the mean annual flow increased at all gages. Cochiti Dam is operated so that the maximum released discharge is 142 to 170 m<sup>3</sup>/s. As a result, operation of the dam only affects flood peaks in excess of 142 m<sup>3</sup>/s (Richard, 2001). Floods with lower peaks are not stored and are allowed to pass through the reservoir.

**Table 1** Comparison of the Rio Grande mean daily discharges before and after closure of Cochiti Dam (November 1973). Pre and post dam values are the mean values for that time period. Average change is the difference between the pre and post dam values expressed as a percentage of the pre-dam value (after Richard, 2001)

Gaging station	Mean annual flow (m <sup>3</sup> /sec)			1-day maximum (m <sup>3</sup> /sec)			High pulse duration (days)		
	Pre-dam	Post-dam	Average change	Pre-dam	Post-dam	Average change	Pre-dam	Post-dam	Average change
Otowi (1895-1996)	41	48	16%	203	173	-15%	13.5	30.3	124%
Otowi/Cochiti (1895-1996)	41	42	3%	218	136	-38%	14.9	23.8	60%
Albuquerque (194301997)	28	42	51%	147	141	-4%	11.3	26.1	131%

The mean sediment concentrations (Fig. 2) were computed from a double-cumulative mass curve of the annual suspended sediment yield and water discharge for the Otowi, Cochiti, Bernalillo, and Albuquerque

gages (Richard, 2001). Otowi and Cochiti represent the sediment concentration flowing into the reach, and Bernalillo/Albuquerque represents the outflowing sediment concentration. The post-dam concentration at Albuquerque is up to two orders of magnitude higher than that at Cochiti, indicating that the tributaries, and/or the channel bed and banks were contributing to the sediment concentration at Albuquerque. The annual average suspended sediment concentration at Cochiti was less than 100 mg/L for 1975-83, and the concentration increased to over 500 mg/L at the Albuquerque gage (Richard, 2001).



**Fig. 2** Summary of changes in the water and sediment flow and channel adjustments of the Rio Grande, Cochiti Reach, NM from 1918 to 1992 (after Richard, 2001)

Statistical procedures (Richter et al., 1996) were used to investigate the impact of the dam on the daily mean suspended sediment concentration data from the Otowi, Cochiti, Bernalillo and Albuquerque gage records. The results of the comparison of the pre-dam with post-dam conditions are presented in Table 2. The greatest impacts of the dam were seen at the Cochiti gage located directly downstream from the dam, where the sediment concentration decreased an average of 99%. Prior to construction of the dam, the suspended sediment concentration at Bernalillo/Albuquerque was typically about 2 times greater than the concentration at Otowi. Following construction of the dam, the average concentration at Albuquerque was less than that at Otowi. The annual mean suspended sediment concentration at the Otowi (upstream of Cochiti dam) gage decreased by 44% from the pre to post dam period (Richard, 2001). Norman (1968) also noted a decline in the sediment concentration at the Otowi and Bernalillo gages following 1958 and suggested that a change in the basin climate from a relatively dry period to a relatively wet period was the reason for the decline in sediment concentration.

**Table 2** Comparison of Rio Grande suspended sediment concentration before and after closure of Cochiti Dam (November 1973). Pre and post dam values are the mean values for that time period. Average change is the difference between pre and post dam values expressed as a percentage of the pre-dam value

Gaging station	Mean sediment concentration (mg/L)			1-day maximum (mg/L)		
	Pre-dam	Post-dam	Average change	Pre-dam	Post-dam	Average change
Otowi (1956-1994)	1,460	819	-44%	20,542	15,097	-27%
Otowi/Cochiti (1956-1994)	1,455	64	-96%	20,542	235	-99%
Albuquerque (1956-1995)	2,823	622	-78%	43,289	11,786	-73%

#### 4 GEOMORPHIC ADJUSTMENTS

The active channel or non-vegetated channel width was measured from digitized coverages of the active channel (U.S. Bureau of Reclamation, 1998) at cross sections every 150 m on average (actual cross section spacing was 67 to 239 m) along the channel and then reach-averaged using one-half the distance to the nearest upstream and downstream cross sections as the weighting factor. The width of the Cochiti reach decreased with time since 1918 as shown in Fig. 2 (Richard, 2001).

Planform maps of the Cochiti reach active channel are presented in Fig. 3. These maps show the non-vegetated active channel from 1918 through 2001 and illustrate the decrease in number and size of mid-channel bars and islands as well as the size of the active channel. Increased sinuosity is evident following dam construction and is most pronounced in reach 2. The planform maps were superposed to measure average lateral movement rates,  $L$ , over the time periods studied. The sums of the changes in the right and left banklines were averaged over the time periods. The results are presented in Fig. 2 and show that the rates of lateral movement have declined since 1918.

To quantify the changes in channel pattern, the sinuosity,  $P$ , and braiding index,  $b$ , were computed from the digitized maps of the active channel. The results of the reach-averaged computations are presented in Fig. 2. The sinuosity,  $P$ , was computed by dividing the thalweg length by the valley length. The sinuosity was low through the entire time period but increased after construction of the dam. The number of channels at each cross-section line was measured from planform maps digitized from aerial photos by the U.S. Bureau of Reclamation (1998). A weighted average of the number of channels per reach,  $b$ , was calculated. The average number of channels remained below two for the entire time period and began to increase after 1985 as mid-channel bars became vegetated from lack of inundation by floodwaters (Richard, 2001).

The Cochiti reach did not exhibit significant changes in channel slope resulting from the completion of Cochiti Dam (Fig. 2). From 1936 to 1972 generally, the entire study reach aggraded more than it degraded (Graf, 1994; Richard, 2001). Fig. 4 illustrates recent (1970-98) changes in cross-section geometry and channel bed elevation. Following construction of Cochiti Dam, the Cochiti reach degraded up to two meters in some regions (Richard, 2001).

A representative median bed-material size was determined for each time period by averaging the available median grain size data. The reach-averaged results are plotted in Fig. 2. There is a shift from a

primarily sand to a gravel bed following construction of Cochiti Dam in 1973. The small variations in grain size between 1918 and 1972 are within the variability observed in the bed of the Rio Grande between storm events and during different periods of the spring-runoff hydrograph (Richard, 2001).

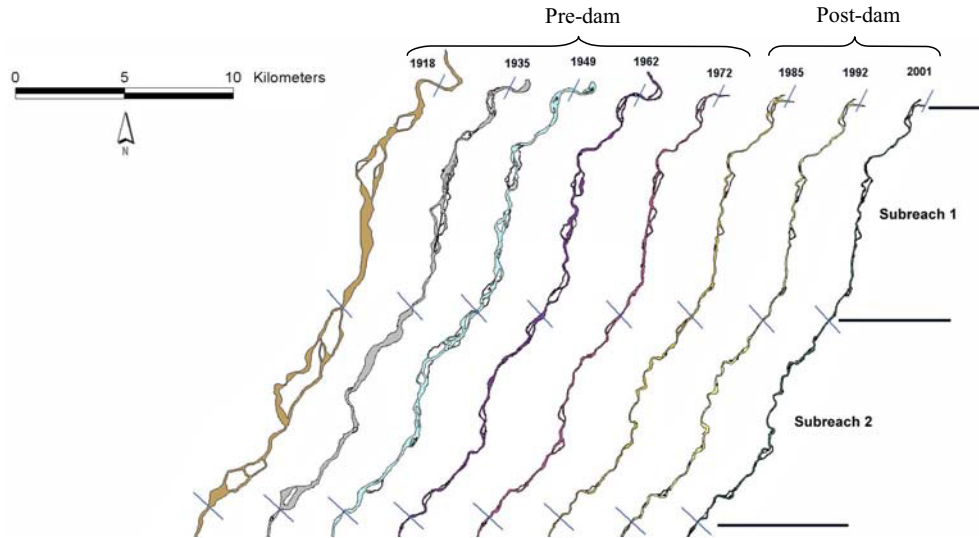


Fig. 3 Example of planform adjustments of the Cochiti Reach, Rio Grande, New Mexico (after Richard, 2001)

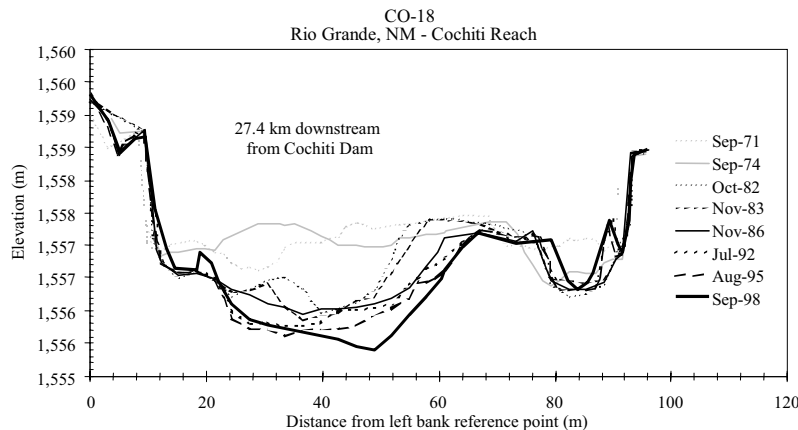


Fig. 4 Example cross-section survey of the Rio Grande downstream from Cochiti Dam. Surveys prior to November 1973 are prior to dam construction (after Leon et al., 1999)

## 5 ECOLOGICAL MANAGEMENT ISSUES

The responses of river ecosystems to dams are complex and depend on a variety of factors including sediment supply, geomorphic adjustments, climate, dam operation strategies, and water temperature and water-quality impacts. The reduction of flood peaks and removal of a sediment supply have implications for both the aquatic and riparian habitat of alluvial river systems. Reduced peak flows and incision of the channel bed result in detachment from the floodplain and reduced lateral migration rates. Changes in the magnitude, frequency, and timing of peak flows affect the diversity of habitat features, which in turn affects the biodiversity and sustainability of the ecosystems.

In 1993, an interagency team of scientists produced a management plan for the Middle Rio Grande valley that addressed management of both the riparian and aquatic habitat, characterized the historic and current conditions, and proposed strategies for improvement of the habitat in the river corridor. The plan identified water as the key variable driving processes in the riparian ecosystem and proposes that water management activities should mimic typical natural hydrographs (Crawford et al., 1993).

The biological management plan proposed that management and improvement of the riparian habitat along the Middle Rio Grande should include: management of livestock grazing, prevention of unmanaged fires, management of recreational activities, use of native plant species in revegetation efforts, enhancement and creation of wetland areas, enhancement and creation of native cottonwood communities, and restriction of the expansion of non-native vegetation (Crawford et al., 1993).

Additionally, in February 1995, the U.S. Fish and Wildlife Service (USFWS) listed the southwestern willow flycatcher (*Empidonax traillii extimus*) as an endangered species, which is a small, grayish-green migratory songbird found only in riparian habitats characterized by dense growths of willows, arrowweed and other species that provide foraging and nesting habitat. The loss of southwestern cottonwood-willow riparian habitat has been the main reason for the decline of the population of the southwestern willow flycatcher (USFWS, 1997).

The decreased spring peak flows and the incision of the bed of the Rio Grande following construction of Cochiti Dam resulted in a river channel that is detached from its floodplain. Over 2 meters of degradation at the Santa Ana Pueblo (about 40 km downstream from the dam) has isolated the cottonwood bosque forest from the floodwaters that are necessary for regeneration of the cottonwoods. In the place of the native cottonwood seedlings, exotic species are thriving, including Russian olive, Siberian elm, and Asian saltcedar, or tamarisk. Beginning in 1996, the Santa Ana Pueblo initiated a restoration project that has resulted in restoration of 115 acres of native grassland and 235 acres of cottonwood bosque through removal of exotic species. The project also included lowering of the floodplain more than one meter in some areas of the 10 km of river within the pueblo. The floodplain-lowering project, which was designed and constructed by the U.S. Bureau of Reclamation included stabilization of the channel bed and mechanical widening of the river channel.

Some of the restoration efforts aimed at the aquatic habitat of the Middle Rio Grande have been influenced by protection the federally-listed endangered Rio Grande silvery minnow (*Hybognathus amarus*). In July 1999, the USFWS designated the Middle Rio Grande from just downstream of Cochiti Dam to the railroad bridge at San Marcial (about 220 km downstream from Cochiti Dam) as critical habitat for the silvery minnow. Alterations in the hydrologic regime and the hydraulic and sediment character of the channel during the last century through construction of diversion dams and channelization have reduced the quality and quantity of habitat for the minnow. The silvery minnow prefers shallow water with a sandy and silty substrate. Recent changes in the channel have produced a narrower, deeper and armored configuration (USFWS, 1999). The channel widening efforts described above will also create backwaters that may provide suitable habitat for the minnow.

## 6 SUMMARY AND CONCLUSIONS

The 45-km long Cochiti reach of the Middle Rio Grande, NM, provided an excellent case study of an alluvial river in response to natural and anthropogenic alterations in water and sediment inflows. The database utilized in this study (Leon et al., 1999) is one of the most comprehensive sets of data available for an alluvial river in the western United States. Daily water discharge records on the Middle Rio Grande began in 1895 and sediment sampling commenced in the 1940's, creating one of the longest hydraulic and sediment records available in the United States. In addition, documentation of channel response began in 1918 with a topographic survey followed by aerial photos in 1935, and commencement of cross-section surveys in the 1930's.

Changes in the water and sediment regime of the Rio Grande and the resulting channel adjustments in both the vertical and lateral dimensions have altered the riparian and aquatic habitats. The floodplain is disconnected from the river channel and no longer floods at peak flows. Regeneration of the native cottonwood forest is affected and encroachment of non-native vegetation is occurring. The channel pattern has shifted from a wide, braided configuration with mid-channel bars, to a single-thread straight and meandering planform. Channel planform changes decreased the available habitat for the Rio Grande silvery minnow, a federally listed endangered species.

Restoration efforts have been aimed at removal and eradication of non-native vegetation, lowering of the floodplain to allow inundation at high flows, and widening of the channel to increase the diversity of in-channel habitat. Biological management plan recommendations suggest that adjustment of the flow regime to more closely mimic the natural hydrograph is an integral piece of protecting and rejuvenating the river ecosystems.

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