

## Stream restoration and environmental river mechanics

PIERRE JULIEN, *Professor of Civil Engineering, Engineering Research Center, Colorado State University, Fort Collins, CO 80523.*  
E-mail: pierre@engr.colostate.edu

GIGI RICHARD, *Assistant Professor, Mesa State College, Grand Junction Colorado, CO 81501, formerly Postdoctoral fellow,*  
*Civil Engineering Dept., Colorado State University, Fort Collins, CO 80523*

JASON ALBERT, *Graduate Student, Civil Engineering Dept., Colorado State University, Fort Collins, CO 80523*

### 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 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.

**Keywords:** Stream restoration; environmental river mechanics; channel geometry; aquatic habitat; river morphology; ecological management; endangered species.

### 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 (Williams and Wolman, 1984; Collier *et al.*, 1996; Friedman *et al.*, 1998; Xu, 1997). Friedman *et al.* (1998)

found from study of 35 dams on large rivers in the Western US that rivers with braided patterns tended to narrow following dam construction, and that meandering rivers experienced reduction in channel migration rate.

The ensuing biological response to dam construction is equally complex and varied and can affect both riparian and aquatic habitats. In some regions riparian vegetation increases (Johnson, 1994), and in others it declines (Johnson, 1998). Reduction of peak flows and disconnection from the floodplain can also encourage encroachment of invasive species, such as saltcedar or tamarisk (Everitt, 1980; Busch and Smith, 1995; Johnson, 1998). Alteration in flow and sediment regime as well as temperature can encourage the success of exotic fish species and harm the native species (e.g., Van Steeter and Pitlick, 1998; USFWS, 1999). Simplification of river channels, which often occurs following dam construction, can reduce the number of backwaters that provide refuge, nursery, spawning and feeding areas for fish (Ward and Stanford, 1989).

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. Williams and Wolman (1984) highlighted the necessity of understanding the unregulated water and sediment regimen as well as changes caused by flow regulation. Such understanding can provide opportunities to differentiate between natural and anthropogenic induced changes.

Using data collected on the Cochiti reach of the middle Rio Grande between 1918 and 1992, this paper presents a case study of river regulation, channel adjustments and restoration efforts. The active adjustment of the Cochiti reach resulting from changes in climate, land use, and 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 relationships 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 kilometers downstream from Cochiti Dam (Figure 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 work (Scurlock, 1998). The dams, built for flood control and sediment detention, were intended to reverse the channel aggradation trend that commenced as much as 11,000 years ago (Sanchez and Baird, 1997).

Later, in the mid-1900's the construction of levees to prevent avulsions into surrounding agricultural land along the river exacerbated the aggradation by confining sediment deposition to a smaller area (Scurlock, 1998; Sanchez and Baird, 1997). Historically the average active channel width was about 275 m and the Cochiti reach exhibited characteristics of braiding with up to four channels at some cross sections (Sanchez and Baird, 1997; Lagasse, 1980, 1981, 1994).

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 kilometers upstream of the City of Albuquerque, Cochiti Dam controls an entire drainage area of about 37,800 km<sup>2</sup> (Bullard and Lane, 1993). The dam traps virtually the entire sediment load from upstream as well as controlling the water discharge (Dewey *et al.*, 1979). 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; Bauer, 1999; Lagasse, 1980).



Figure 1 Location map Cochiti Reach, Rio Grande, New Mexico. Locations of major tributaries and USGS gaging stations are indicated.

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 by the U.S. Geological Survey (USGS). In 1895, the Otowi gaging station (Figure 1) was established and provides the longest record of discharge and suspended sediment data used in this study. The combination of severe flooding and sedimentation along with irrigation needs in the middle Rio Grande valley in the early 1900's prompted state and federal agencies including the U.S. Army Corps of Engineers (the Corps), the U.S. Bureau of Reclamation (USBR), the USGS and the Soil Conservation Service (SCS, now the Natural Resources Conservation Service) to begin intensive surveys of the river. 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 1992. 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

#### 3.1 Hydrologic regime

Stream gage data along the Cochiti reach are available from 1895 to 1997 at several 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 Figure 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. The San Felipe gage (1927-present), the Bernalillo gage (1929–1969) and the Albuquerque gage (1942–1997) are located further downstream. 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 are presented in Figure 2 from 1918 to 1995.

Figure 3 shows the post-dam annual maximum daily mean discharge for the Otowi (above Cochiti dam) and Cochiti (below Cochiti dam) gages. Attenuation of the peak flows is evident (Richard, 2001).

Statistical procedures (Richter *et al.*, 1996) were used to compare the water discharge records prior to and following

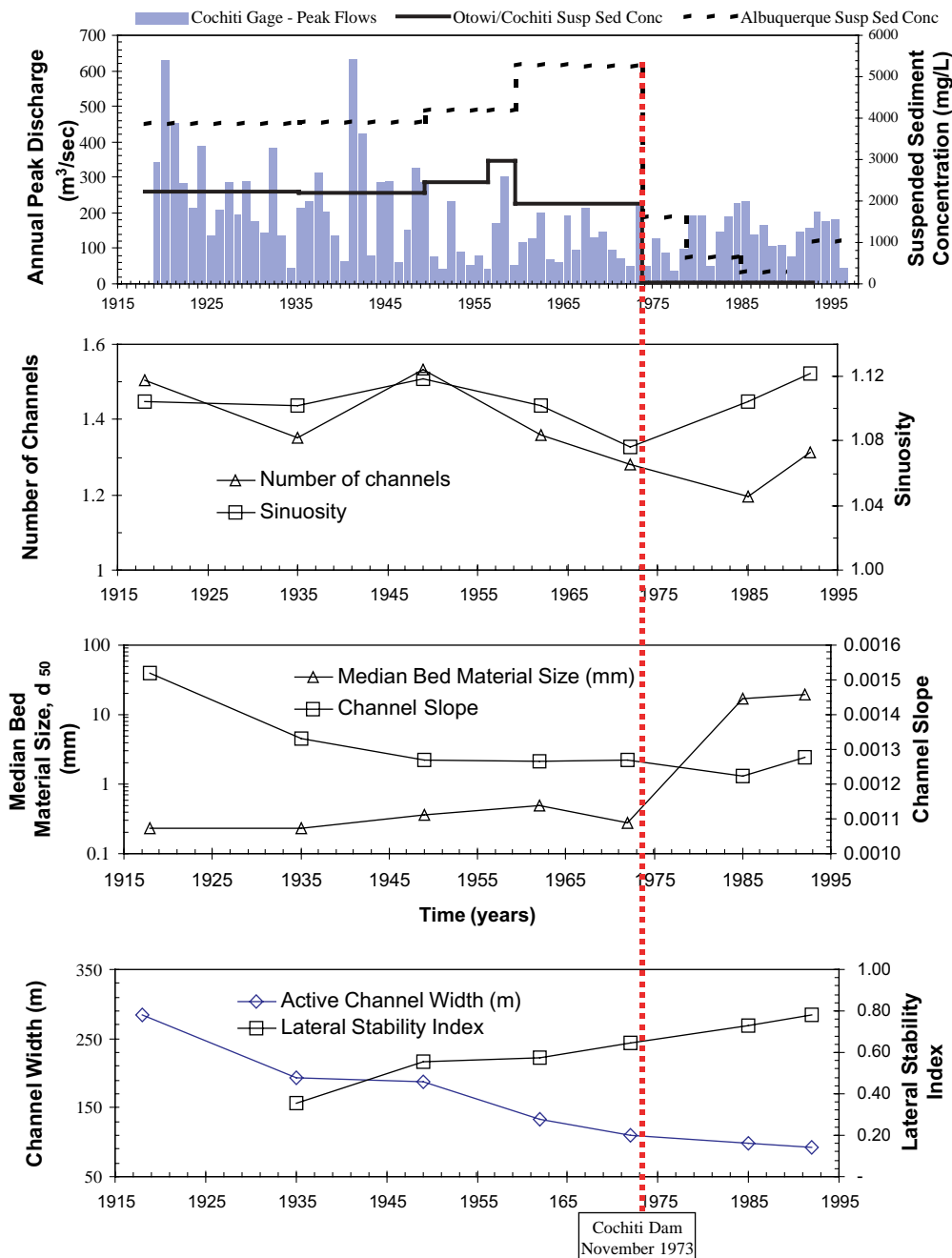


Figure 2 Summary of changes in the water and sediment flow and channel adjustments of the Rio Grande, Cochiti Reach, NM from 1918 to 1992 (after Richard, 2001).

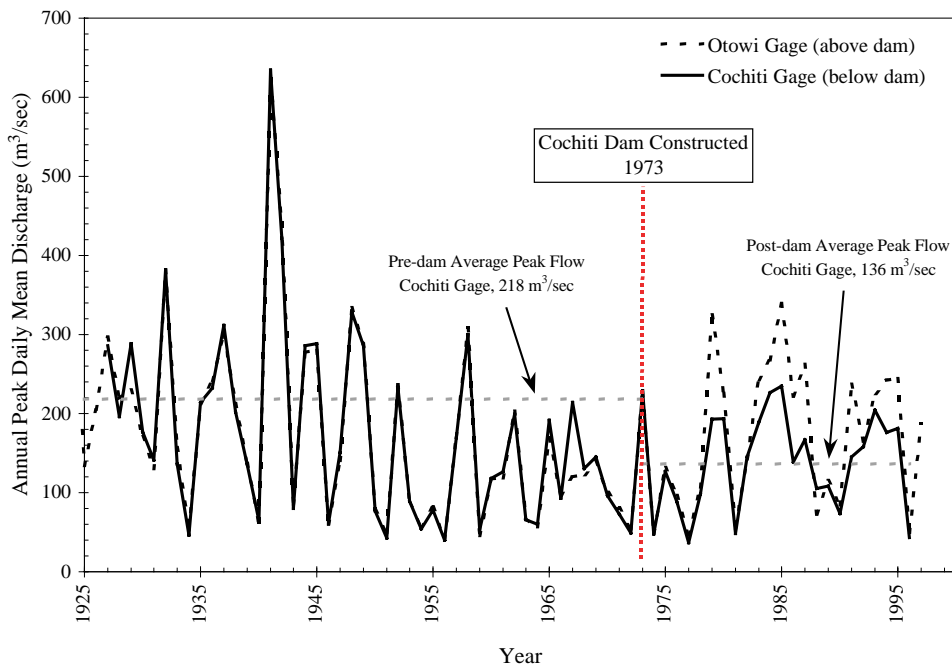


Figure 3 Post-dam annual maximum daily mean discharge at Otowi and Cochiti gages.

Table 1 Comparison of the Rio Grande mean daily discharges in  $\text{m}^3/\text{s}$  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 means expressed as a percentage of the pre-dam value (after Richard, 2001).

Gaging station	Mean-annual flow ( $\text{m}^3/\text{sec}$ )			1-day maximum ( $\text{m}^3/\text{sec}$ )			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 (1943–1997)	28	42	51	147	141	–4	11.3	26.1	131

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 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  $\text{m}^3/\text{s}$ . As a result, operation of the dam only affects flood peaks in excess of 142  $\text{m}^3/\text{s}$  (Richard, 2001).

### 3.2 Sediment supply

The suspended sediment data used in this study include USGS gaging station records from Otowi (1955–1995),

Cochiti (1971–1988), Bernalillo (1955–1969) and Albuquerque (1969–1995) gaging stations as reported in Leon *et al.* (1999) combined with sediment data from Pemberton (1964), Nordin (1964), Nordin and Beverage (1964 and 1965), Nordin and Culbertson (1961), and Culbertson and Dawdy (1964).

The mean annual sediment concentrations were compared for pre and post dam conditions at the Otowi, Cochiti and Bernalillo gages using the USGS gage record (Leon *et al.*, 1999). The average annual sediment concentrations for Otowi, Cochiti, Bernalillo, and Albuquerque are plotted in Figure 2. 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).

Mass and double mass curves can be used for the long-term analysis of trends and changes in sediment transport

characteristics of rivers (Julien, 1998 and 2002). In terms of suspended sediment load, Figure 4 shows the mass curves of the Rio Grande at Albuquerque and Bernalillo. It is shown that the mean annual suspended sediment load decreased from 3.6 to 1.0 million tons per year due to the construction of the dam. Figure 5 also shows the double mass curves of the Rio Grande at Albuquerque and Bernalillo. The slope of the double mass curves indicates that the average suspended sediment concentration decreased from 3740 to 670 mg/L as a result of Cochiti dam.

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. It is interesting that the annual mean suspended sediment concentration at the Otowi gage decreased by 44% from the pre to post dam period. Otowi gage is located upstream of Cochiti Dam, so this decline is a result of other factors possibly including climatic shifts, land use changes and other river regulation (Richard, 2001).

#### 4 Geomorphic adjustments

##### 4.1 Lateral adjustments

##### 4.1.1 Channel width

The active channel width was measured from digitized coverages of the active channel delineated by the USBR's GIS and Remote Sensing Group from aerial photos and topographic surveys (USBR, 1998). The non-vegetated active channel width is the total channel width between the outermost banklines minus the width of the mid-channel vegetated bars and islands. The

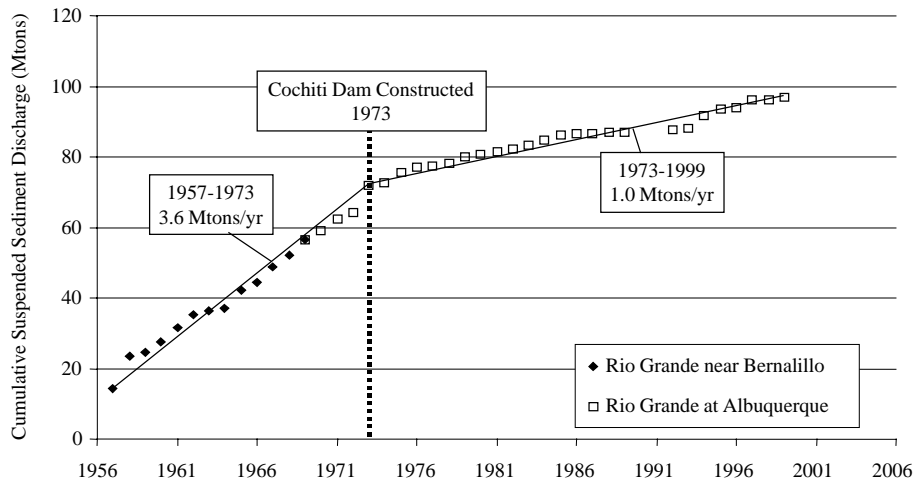


Figure 4 Mass curves of suspended sediment discharge at Bernalillo and Albuquerque (after Albert, 2004).

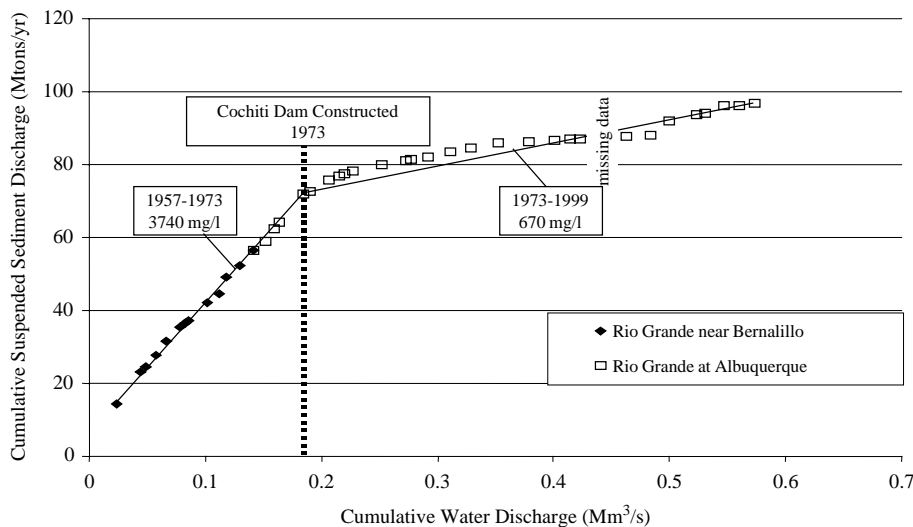


Figure 5 Double mass curves of suspended sediment discharge at Bernalillo and Albuquerque (after Albert, 2004).

Table 2 Comparison of Rio Grande suspended sediment concentration (mg/L) 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 means 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 (1956–1984)	1,455	64	–96	20,542	235	–99
Albuquerque (1956–1995)	2,823	622	–78	43,289	11,786	–73

active and total channel widths were measured at cross sections every 500 meters along the channel and then reach-averaged using one-half the distance to the nearest upstream and downstream cross sections as the weighting factor. Figure 2 illustrates the changes in active channel width with time and distance downstream. The width of the Cochiti reach decreased with time since 1918 (Richard, 2001).

#### 4.1.2 Channel planform

Planform maps of the Cochiti reach active channel are presented in Figure 6. These maps show the non-vegetated active channel from 1918 through 1992 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. Channel pattern is often considered to be a function of stream power, or of a slope-discharge relationship combined with sediment supply (Bledsoe, 1999). Accordingly, the channel pattern of the Cochiti

reach shifted as flow energy and sediment supply changed from 1918 to 1992 (Richard, 2001).

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 Figure 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 USBR (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 generally declined during the entire study period (Richard, 2001).

#### 4.1.3 Lateral stability

Using the overlay GIS coverages of the active channel for different years, the percentage of the active channel that remained

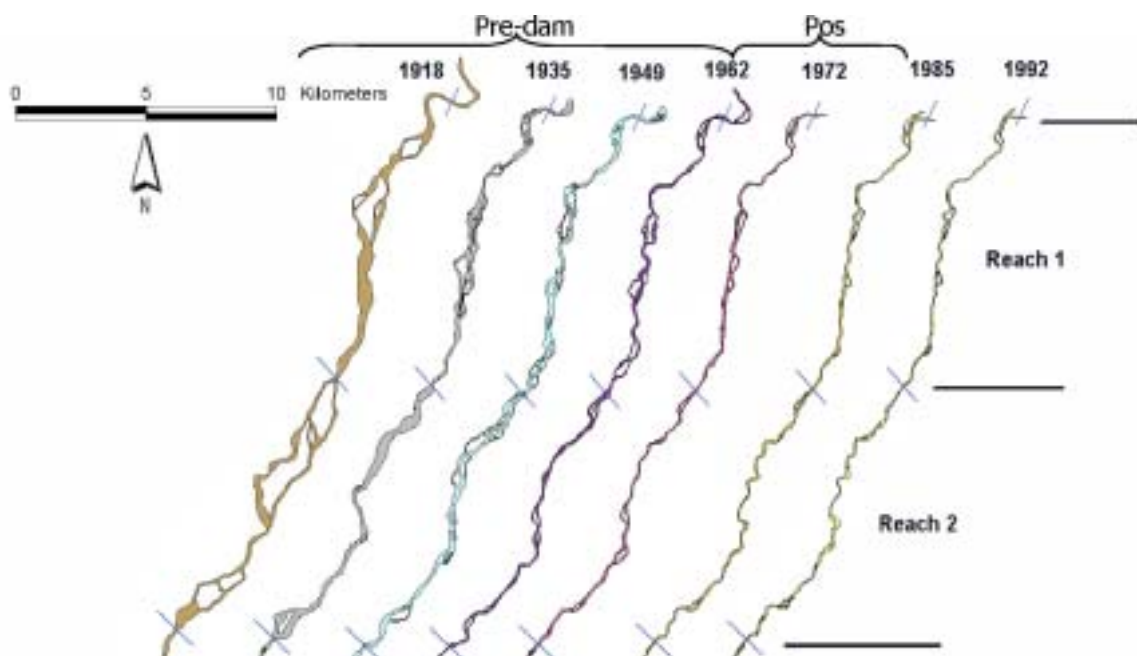


Figure 6 Example of planform adjustments of the Cochiti Reach, Rio Grande, New Mexico (after Richard, 2001).

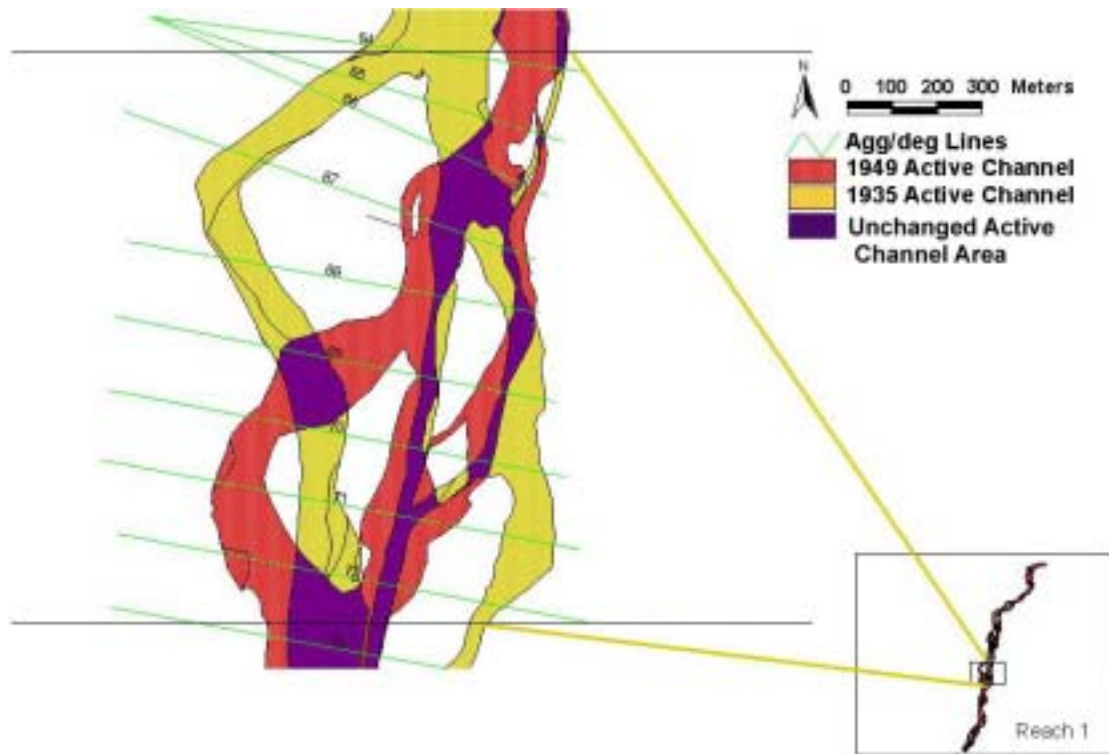


Figure 7 Lateral stability index = Unchanged active channel area/previous active channel area (after Richard, 2001).

in the area of the previous active channel was measured as illustrated in Figure 7:

$$\text{Lateral Stability Index} = \frac{\text{Unchanged Active Channel Area}}{\text{Previous Active Channel Area}} \quad (1)$$

A value close to one indicates that the channel has not moved and is relatively stable. Small values of the index indicate that the channel has moved from its original location. Figure 2 shows the values of the lateral stability index for the entire time period for the four reaches. The trend is toward increasing stability in all reaches through the entire study period (Richard, 2001).

#### 4.2 Vertical adjustments

The Cochiti reach did not exhibit significant changes in channel slope resulting from the completion of Cochiti Dam (Figure 2). From 1936 to 1972 generally, the entire study reach aggraded more than it degraded, which is supported by observations of the channel during this time period (Graf, 1994). Figure 8 illustrates 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).

##### 4.2.1 Bed material

Prior to the construction of Cochiti Dam, the size of the bed material did not change significantly with time. Rittenhouse (1944, p. 165), when discussing the Rio Grande from Cochiti to the mouth of the Jemez River, states: "In the upper part of the Middle Valley the Rio Grande channel deposits consist of fine to

medium sands overlying a bed pavement of cobbles and pebbles. Downstream the gravel becomes less abundant and below Albuquerque seldom constitutes more than a few per cent in the upper 5 feet of the deposits." Nordin and Beverage (1965) corroborate these observations. Between Cochiti and Albuquerque, the channel deposits consisted of fine to medium sands overlying a bed pavement of cobbles and pebbles. The gravel became less abundant further downstream from Cochiti. Galisteo Creek contributed notably coarser sediment than that in the main stem, and the Jemez River bed sediment was similar to that of the main stem.

A representative median grain size was determined for each time period and reach by averaging the available median grain size data. The reach-averaged results are plotted in Figure 2. There is a shift from a primarily sand-sized 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).

## 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 later migration rates. Changes in the magnitude, frequency and timing of peak flows

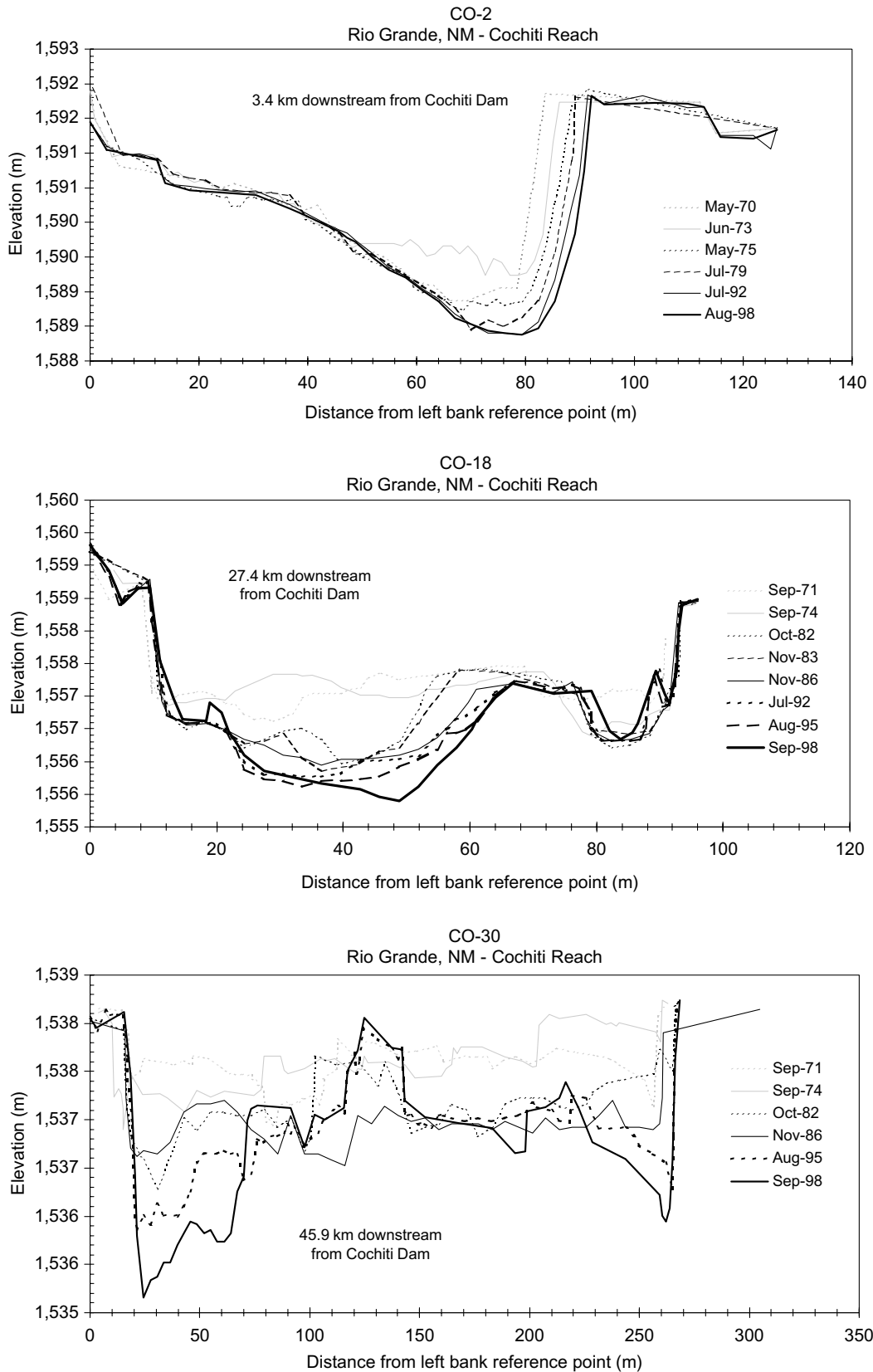


Figure 8 Cross-section surveys of the Rio Grande downstream from Cochiti dam. Surveys prior to November 1973 are prior to dam construction (after Leon *et al.*, 1999).

affect the diversity of habitat features, which in turn affects the biodiversity and sustainability of the ecosystems (Poff *et al.*, 1997; Ward and Stanford, 1995; Ward *et al.*, 1999; Power *et al.*, 1996). Generally, successful restoration strategies downstream

of dams should include: restoration of peak flows to reconnect channel and floodplain habitats, stabilization of baseflows, and restoration of seasonal temperature pattern (Stanford *et al.*, 1996).

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).

### 5.1 Riparian habitat

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. This species 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 (Hanscom, 2001).

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. Similar restoration efforts including non-native vegetation removal efforts, revegetation with native species and river channel widening and floodplain lowering are being initiated further downstream at the Sandia Pueblo, Cities of Albuquerque, Belen, and Socorro, and in the Bosque del Apache wildlife refuge (Hanscom, 2001).

### 5.2 Aquatic habitat

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 U.S. Fish and Wildlife Service (USFWS) designated the Middle Rio Grande from just downstream of Cochiti Dam to the railroad bridge at San Marcial 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 (Hanscom, 2001).

## 6 Summary and conclusions

The 45-kilometer long Cochiti reach of the Rio Grande, NM, provided an excellent case study in response of an alluvial river 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.

### 6.1 Water discharge

A decline in annual peak flows since 1895 occurred independently of Cochiti Dam as evidenced by the significant ( $p < 0.02$ ) negative trend in peak flows at the Otowi gage located upstream from Cochiti Dam. Peak flow attenuation caused by the dam also increased the peak flow period (high pulse duration) an average of 60 to 130% from the pre-dam to post-dam periods. The mean annual flow increased from the pre-dam (1895–1973) to the post-dam (1974–96), from 3% at the Cochiti gage to 51% at the Albuquerque gage.

### 6.2 Sediment supply

Completion of Cochiti Dam (1973) resulted in a 99% reduction in sediment concentration flowing into the study reach. The suspended sediment concentration also declined around this time at the Otowi gage located upstream from the dam. The impact from the dam is less pronounced at the Albuquerque gage indicating another source of sediment, either tributary inflow or erosion of bed and banks.

### 6.3 Vertical response

Vertical response to pre-dam changes in water and sediment inputs consisted of small aggradational changes in the bed and

minor slope adjustments. The bed of the entire Cochiti reach was primarily sand and reaches 1 and 2 exhibited a bi-modal distribution with gravel overlain by fine and medium sand (Rittenhouse, 1944; Nordin and Culbertson, 1961). Following construction of the dam, the lower peak flows combined with depleted sediment supply resulted in degradation of up to 1.9 meters and coarsening of the bed to gravel/cobble size.

#### 6.4 Lateral response

Lateral changes in the river were measured from the digitized coverages of the non-vegetated active channel from 1918 through 1992. Channel width declined during the entire study period by as much as 76%. The channel pattern shifted from a braided, multi-channel pattern to a meandering, single-thread pattern. Post-dam lateral responses were not as pronounced as the vertical changes. The sinuosity of the channel increased during the post-dam period and some channel widening occurred due to bank erosion. Use of a lateral stability index showed that the channel became less mobile and more stable as it continued to occupy more of the same channel area during the study period.

#### 6.5 Ecological response

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.

#### Acknowledgements

This study was completed at the Engineering Research Center at Colorado State University. Financial support by the U.S. Bureau of Reclamation is gratefully acknowledged. Deepest thanks are extended to D.C. Baird for his encouragement and support. Our gratitude is extended to C. Leon and T. Bauer for their efforts in development of the database. The technical assistance of V. Sanchez, P. Makar, J. Oliver, and T. Massong during this study is also appreciated.

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