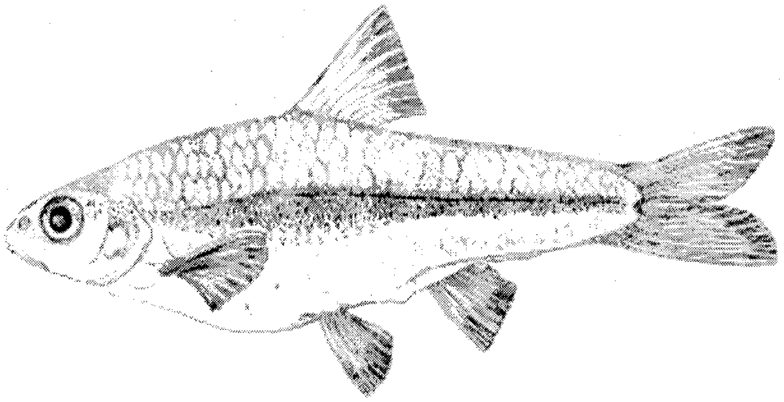
SPECIAL PUBLICATIONS

Museum of Texas Tech University

NUMBER 46 12 May 2003

AQUATIC FAUNA OF THE NORTHERN CHIHUAHUAN DESERT



CONTRIBUTED PAPERS FROM A SPECIAL SESSION WITHIN
THE THIRTY-THIRD ANNUAL SYMPOSIUM OF
THE DESERT FISHES COUNCIL

HELD
17 NOVEMBER 2001
AT
SUL ROSS STATE UNIVERSITY, ALPINE, TEXAS

EDITED BY
GARY P. GARRETT AND NATHAN L. ALLAN

HYDROLOGY AND GEOMORPHOLOGY OF THE RIO GRANDE AND IMPLICATIONS FOR RIVER REHABILITATION

John C. Schmidt, Benjamin L. Everitt, and Gigi A. Richard

ABSTRACT

The Rio Grande watershed includes a northern and southern branch that have very different hydrologic regimes. The natural flood regime of the northern branch is snowmelt driven, and that of the southern branch, the Río Conchos, is driven by summer rainfall. Downstream from the confluence of the two branches, near Presidio, Texas, the natural pattern of high and low flow was dominated by runoff from the Conchos basin between July and the following March prior to the construction of large dams. Dams and diversions greatly altered the natural hydrologic regime of both branches. The magnitude of the 2-year recurrence flood of the Rio Grande at El Paso, on the northern branch, declined by 76% after 1915. The magnitude of the 2-year recurrence flood downstream from Presidio was reduced by 49% after 1915.

Dams and diversions have also significantly altered the natural sediment flux, and significant geomorphic adjustments of the channel have resulted. The northern branch includes reaches where degradation or aggradation has occurred during the past century. Reaches immediately downstream from dams have degraded beds and narrowed widths. Further downstream, the channel bed has aggraded, and the channel width has narrowed. Channelization and levee construction have occurred in some of these same river segments.

Restoration, defined as returning an ecosystem to a close approximation of its condition prior to disturbance, is impossible on the main stem of the Rio Grande because of current institutional demands on stream flow and the extent of alteration of the floodplain. Rehabilitation, defined as returning essential physical and ecological functions to a degraded ecosystem, is a more appropriate goal for the Rio Grande. In light of the diverse styles of twentieth-century channel adjustments that have occurred throughout the basin, different river segments must be assigned different rehabilitation goals.

INTRODUCTION

The Rio Grande has the second longest river course and had the sixth largest mean sediment discharge in North America before the continent was settled extensively by Europeans (Meade et al., 1990). Human activity has disrupted the natural flux of water and sediment. Large dams store floods for subsequent diversion, and these dams also trap sediment. The total volume of stream flow has been reduced, and the magnitude of floods in some parts of the Rio Grande have been reduced by more than 50%. Meade et al. (1990) estimated that annual sediment delivery to the Gulf of Mexico decreased from about 30 x 10^6 tonnes in 1700 to about 0.8 x 10^6 tonnes in 1980. These changes have caused significant adjustments of the channel of the Rio Grande. Historically, the Rio Grande had a mobile bed and erodible banks, and the channel changed from year to year. Today's channel is smaller, more stable, changes less from year to year, and infrequently inundates its former floodplain.

The riverine ecosystem has adjusted to these changes in ways that do not benefit some native species. Inundation of the floodplain, which now occurs rarely in some segments, is necessary for recruitment in the riparian forest that lines the Rio Grande (Moles et al., 1998). Non-native salt cedar (*Tamarix* sp.) has widely colonized abandoned alluvial surfaces of the once-wider channel. The endangered Rio Grande silvery minnow (*Hybognathus amarus*) is adapted to the former wide shallow braided channel and associated habitats, and its population has declined greatly in response to channelization and diminished flows.

The purpose of this review paper is to describe hydrologic and geomorphic conditions of the river during the past century and to summarize changes in the water and sediment flux. We describe some of the geomorphic adjustments of the channel and its floodplain that have occurred during the past century, emphasizing channel changes downstream from the large dams on the northern branch: Cochiti Dam and Elephant Butte and Caballo dams. These changes in hydrology, sediment transport, and physical characteristics of the channel and floodplain affect the aquatic and riparian ecosystem of the river. We conclude by commenting on the implications of these physical changes to development of a basin wide strategy for rehabilitating physical attributes and processes of the riverine ecosystem.

Description of the Rio Grande Drainage Basin

The hydrologic regime of the Rio Grande downstream from Presidio, Texas, results from the combined flow of northern and southern branches of the river (Figure 1). The drainage basin of the northern branch, called the Rio del Norte by Spanish explorers, comprises about two-thirds of the total watershed area upstream from Presidio. The flow of this branch, called the Rio Grande in the United States and the Rio Bravo in Mexico, is primarily contributed by snowmelt in the southern Rocky Mountains, and this branch had its annual peak flow in late spring, prior to the construction of dams. The Río Conchos, whose headwaters are in the Sierra Madre Occidental, is the southern branch. Although the Río Conchos basin is smaller than that of the northern branch, its mean annual runoff is much larger, and this branch has its maximum flows in late summer.

Several names are used to describe the different parts of the northern branch. The basin upstream from Elephant Butte Reservoir was referred to as the Upper Basin by Dortignac (1956) and the Northern Rio Grande by Graf (1994). Scurlock (1998) defined the segment between the Rio Chama and Elephant Butte Reservoir as the Middle Basin and many studies of this segment refer to it as the Middle Rio Grande, distinguishing it from the Upper Rio Grande that occurs upstream from the Rio Chama. For our purposes, we use the term northern branch when referring to the entire basin upstream from the Río Conchos, and we refer to shorter river reaches by specific geographical names.

The river flows through a series of structural basins, where the alluvial valley is very wide, separated by intervening canyons where the valley is narrow. The occurrence of wide alluvial valleys and intervening narrow canyons is important in analyzing channel adjustment to the regulation of stream flow and sediment flux. Rivers typically have lower gradients in wide alluvial valleys where they have large floodplains and meandering channels. Typically, channels narrow to greater extents in alluvial segments with flat gradients, and channel adjustments are less in narrow canyons (Grams and Schmidt, 2002).

The northern branch's headwaters are in the San Juan, Sangre de Cristo, and Jemez mountains of Colorado and New Mexico (Figure 1). The most upstream beginnings of stream flow occur near Stoney Pass in the San Juan Mountains. The Rio Grande leaves the San Juan Mountains near Del Norte, Colorado, and enters the San Luis Valley of south-central Colorado. This valley is a deep structural basin at the northern end of the Rio Grande Rift that is filled with more than 9,000 m of alluvium. The Rio Grande has a low gradient and has not significantly incised its channel through these sediments. Thus, the Rio Grande is easily diverted onto adjoining valley lands here, and irrigation is extensive.

South from the San Luis Valley, the Rio Grande enters a narrow canyon through the Taos Plateau – the Canon del Rio Grande. Further downstream are Espanola Basin, White Rock Canyon, and the Santo Domingo-Albuquerque-Belen basin. The large basins of central New Mexico have been aggrading for as much as 11,000 years (Sanchez and Baird, 1997), and the Rio Grande channel is not significantly incised into the sediments of the alluvial valley. Aggradation in these basins continues to the present. Two basins in southern New Mexico – Engle and Las Palomas Valleys – are partially inundated by Elephant Butte and Caballo reservoirs, respectively. The releases from these reservoirs are diverted for agriculture in the Mesilla and El Paso/Juarez valleys further downstream.

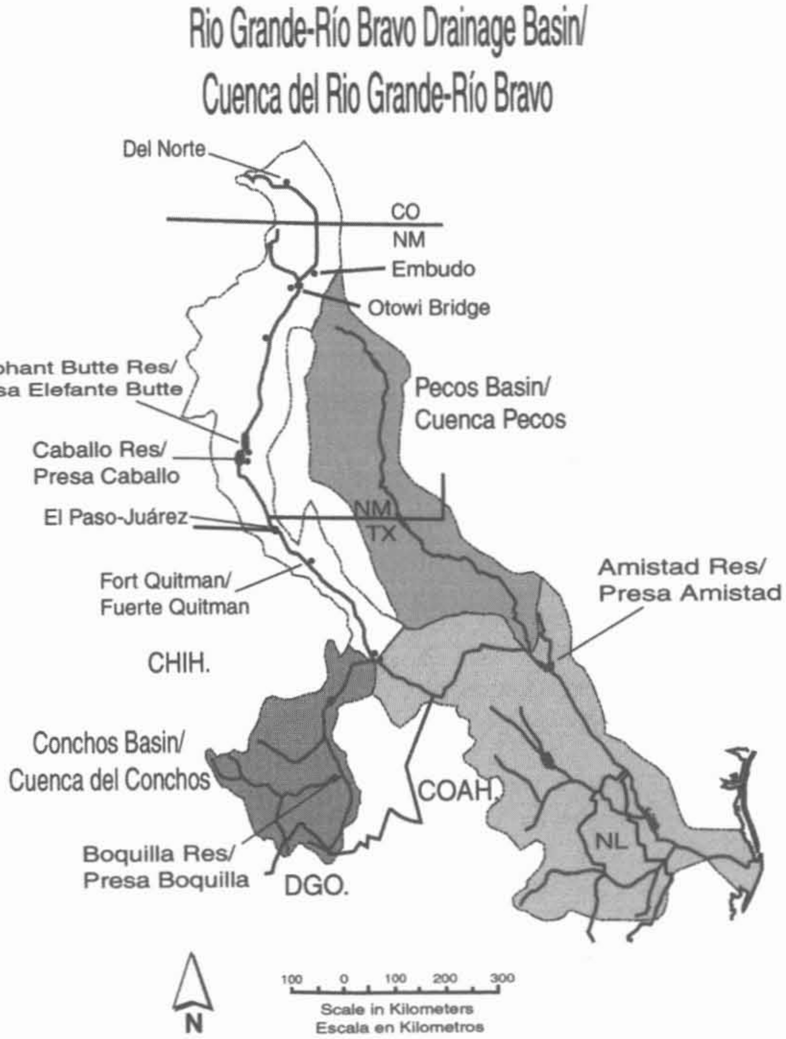


Figure 1. Map showing entire drainage basin of the Rio Grande/Rio Bravo.

The El Paso/Juarez valley is about 136 km long, 16 km wide in places, and extends downstream to approximately Fort Quitman, Texas (Stotz, 2000). Downstream from Fort Quitman, the Upper Canyon segment includes 200 km where there are 11 different canyons and as many intervening alluvial valleys. The longest individual canyon is 14.7 km long, and canyon reaches comprise about 24% of the Upper Canyon segment upstream from Candelaria. The Upper Canyon segment also includes the Presidio Valley, which is about 120 km long between Candelaria and Presidio. The Presidio Valley is less than 5 km wide. The river is mostly channelized and leveed here. The Rio Grande is joined by the Río Conchos near Presidio.

Downstream from the Río Conchos, the Rio Grande flows through alternating alluvial and confined reaches in the Big Bend section, including four narrow canyons that are popular for recreational boating – Colorado, Santa Elena, Mariscal, and Boquillas canyons (Aulbach and Gorski, 2000). The Lower Canyons extend to the headwaters of Amistad Reservoir (Aulbach and Butler, 1998).

Downstream from Amistad Reservoir, the Rio Grande exits its canyons and flows across the Gulf Coast piedmont. With the added contributions of the Pecos and Devils Rivers, it still occasionally lives up to its names "Grande" (Big) and "Bravo" (Wild). Peak flows from occasional autumn hurricanes exceed 25,000 m^3/s. Downstream from Laredo, Texas, the Rio Grande wanders across its delta plain of fine-grained alluvial deposits.

THE HISTORY OF WATER DEVELOPMENT

Agricultural use of the Rio Grande in New Mexico began in pre-history (Table 1). Pueblo peoples were utilizing ditch irrigation on a limited scale at the time of Spanish exploration in 1591 (Scurlock, 1998). Graf (1994) speculated that, "Diversion works on the main stream probably consisted of brush and boulder structures ... [that] probably washed away with each spring flood." Spanish and Mexican settlers in New Mexico expanded irrigation on floodplains and terraces of the Rio Grande, and the area of irrigated farming steadily increased in New Mexico until it reached a peak of 50,500 ha in 1880 (Sorenson and Linford, 1967, cited by Scurlock, 1998). Ditch irrigation began in the mid-1600s in the El Paso/Juarez Valley and direct diversions of the main channel in this valley were underway by at least the late 1700s (Stotz, 2000). Water was being diverted from the Río Conchos for use at the presidio in the Presidio Valley by 1750.

Of the 63 dams built in the northern branch watershed prior to 1916, 48 were in Colorado, and their purpose was to facilitate irrigation in the San Luis Valley. Between 1855 and 1893, 8 dams were built there whose cumulative reservoir storage was 4.08×10^6 m^3 (data from U. S. Army Corps of Engineers, 1996). Between 1894 and 1915, 55 more dams were built in the northern branch watershed, and the cumulative reservoir storage increased more than 100 times to about 486×10^6 m^3.

Depletions of stream flow caused by irrigation withdrawals have been substantial for more than a century. Kelley (1986) estimated that more than half the summer stream flow from central and northern New Mexico between 1890 and 1893 was consumed by irrigation. Kelley (1986) also estimated that 74% of the Rio Grande's stream flow was lost to seepage, evapotranspiration, and irrigation between the Mesilla Valley in southern New Mexico and Presidio during the same period. Without irrigation, Kelley (1986) estimated that losses would only have been about 35%. Between 1936 and 1953, the average annual depletion in the San Luis Valley was 9.9×10^8 m^3, and annual depletions ranged from about 6.2×10^8 m^3 in dry years to more than 12.3×10^8 m^3 in wet years. Depletions in central New Mexico were of a similar magnitude during this period (Thomas et al., 1963).

Elephant Butte Dam was completed in 1916, and had an initial capacity of about 2.93×10^9 m^3. The dam was built to control floods and ensure the delivery of irrigation water to southern New Mexico and to Mexico. At the time of completion, Elephant Butte Reservoir had a capacity of 2.5 times the mean annual discharge and was the largest reservoir in the world. Its construction increased the total reservoir storage in the basin by more than 6 times to $3,390 \times 10^6$ m^3 (Figure 2).

Small reservoirs, low head main stem diversion structures, levees, and channelization works were built throughout central New Mexico in the 1920s (Scurlock, 1998). These construction activities were directed by the Middle Rio Grande Conservancy District, organized in 1925. Diversion dams directed stream flow into extensive irrigation canals at Cochiti, Angostura, Isleta, and San Acacia. The construction of levees to prevent avulsions into surrounding agricultural lands along the river exacerbated the aggradation by confining sediment deposition to a smaller area (Scurlock, 1998; Sanchez and Baird, 1997). The construction of levees, begun in the 1920s, became a comprehensive channelization scheme that was completed in central New Mexico by the early 1960s (Graf, 1994).

El Vado Dam on the Rio Chama was completed in 1935 for flood control and irrigation supply. Caballo Dam, immediately downstream from Elephant Butte, was completed in 1938, and total basin wide reservoir storage increased to 4.37×10^9 m^3. Together, Elephant Butte and Caballo completely stored the annual snowmelt flood in every year between 1915 and 1941, and there were no flood releases downstream. The years 1941 and 1942 had unusually large runoff, however, and the dams and levees of that time were not able to control those floods.

Table 1. Dams and other structural modifications in the Rio Grande basin upstream from Amistad Reservoir.

Date	Event
1200-1850s	Pueblo, Spanish, and Mexican temporary diversion structures in the Rio Grande channel in New Mexico with gradual expansion of irrigated area in central New Mexico
1659	Founding of mission at Paso del Norte, temporary diversion and headgate constructed
1899	Cordoba Island cut-off, El Paso-Juarez
1916	Elephant Butte Dam completed
1925	Middle Rio Grande Conservancy District organized
1925-1935	Diversion dams at Cochiti, Angostura, Isleta, and San Acacia completed, 290 km of riverside drains and 260 km of interior drains constructed in irrigated fields of central New Mexico
1926	Salt cedar planted for erosion control in Rio Puerco basin
1933	Channelization through Mesilla Valley to El Paso
1935	El Vado Dam on the Rio Chama completed
1938	Caballo Dam completed
1938	Rectification and channelization, El Paso to Ft Quitman
1941 and 1942	Large floods cause 27 levee breaks near Albuquerque
1940s	Rio Puerco sediment control structures and revegetation
1950s and later	Channelization of the Middle Rio Grande
1950s?	Sediment control dams on tributary arroyos between Elephant Butte and Fort Quitman
1963	Abiquiu Dam completed
1967	Settlement of the "Chamizal" boundary dispute and construction of concrete-lined channel separating El Paso and Juarez
1969	Amistad Dam completed
1971	Heron Dam completed
1971	Transbasin diversion from the San Juan River
1973	Cochiti Dam completed

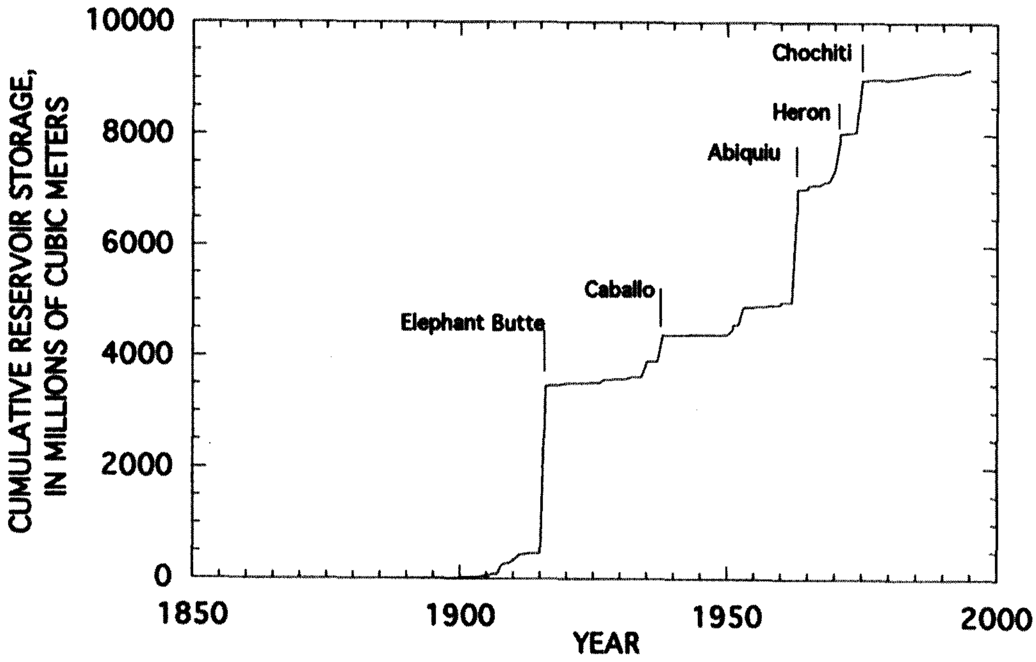


Figure 2. Graph showing time series of cumulative reservoir storage in the northern branch.

Abiquiu Dam was built on the Rio Chama in 1963 as part of the Colorado River Storage Project, and diversions from the San Juan River into the Chama basin began in 1971. Today, Abiquiu is the second largest dam in the northern branch watershed.

Cochiti Dam on the Rio Grande, located 65 km upstream from Albuquerque, was completed in 1973. It provides the largest flood control storage volume on the northern part of the main stem (Bullard and Lane, 1993). The dam was completed in November 1973 for flood control and sediment detention (U.S. Army Corps of Engineers, 1978) and traps virtually the entire sediment load from upstream (Dewey et al., 1979).

Large dams have also been constructed on the Río Conchos, creating La Boquilla Reservoir in 1913, Francesco I. Madera Reservoir in 1947, and Luis L. Leon Reservoir in 1967. The largest reservoirs in the Rio Grande basin are located downstream from Presidio: Falcon (completed in 1954; 3.18 x 10^9 m^3) and Amistad (completed in 1969; 5.13 x 10^9 m^3). The cumulative size of Amistad and Falcon reservoirs is greater than the total storage of all the reservoirs of the northern branch, illustrating the substantially greater stream flow that is regulated in the downstream parts of the Rio Grande/Río Bravo.

TREATIES

The international position of the Rio Grande has played a significant role in its physical and hydrologic history, as well as its cultural history (Mueller, 1975). Under the Treaty of 1848, the segment between El Paso and the Gulf of Mexico was made the boundary between the two countries. Mapping of the river boundary was completed in 1852 (Emory, 1857). The active nature of the river was not anticipated, and within 30 years parts of the river had wandered kilometers from its 1852 course and dozens of oxbows were abandoned, making redefinition of the boundary necessary. The Treaty of 1884 included specific language providing for a moveable boundary, following the natural migration of the channel by erosion and accretion, but remaining fixed in the abandoned channel in the event of avulsion. The treaty also provided for additional mapping of channel changes, and restricted artificial modification of the channel.

The Treaty of 1970 provided for the first complete mapping of the 2000-km river boundary since 1852. The treaty strengthened restrictions against artificial modification to include levees on the flood plain that might raise flood heights on the opposite bank.

The Water Treaty of 1906 apportioned the flow of the northern branch, and provided for storage and delivery of Mexico's allotment via the Rio Grande Project. The 1944 Water Treaty allocated the water of the Rio Grande downstream from Presidio and gave the International Boundary and Water Commission authority to oversee measurement and distribution of stream flow. The treaty provided for the construction of international storage reservoirs. Reflecting the wartime emphasis on agriculture and industry, the treaty established the following priority for use of stream flow: domestic and municipal uses, agricultural and stock-raising, hydroelectric power generation, other industrial uses, navigation, fishing and hunting, and other beneficial uses.

HYDROLOGY OF THE BASIN PRIOR TO 1915

The records of floods and droughts on the northern branch are preserved in the journals and notes of explorers and residents of the basin. Scurlock (1998) determined that there were at least 50 major floods exceeding 280 m^3/s in New Mexico between 1849 and 1942 and 51 floods in the El Paso/Juarez Valley since 1846. Twice as many known floods occurred in the 1800s than in the 1600s or 1700s. Scurlock (1998) and Stotz (2000) suggested that environmental degradation may have contributed to the increase in flood frequency in the 1800s, but Graf (1994) suggested that regional climate change was a more likely cause. The largest flood occurred in 1828 and had an estimated discharge of about 2,830 m^3/s. During this flood, the entire Rio Grande valley was inundated from Albuquerque to at least El Paso. Other very large floods occurred in 1872 and 1884.

The gauged flow of the Rio Grande prior to 1915 reflected the impacts of irrigation withdrawal in the San Luis Valley and central New Mexico. The northern branch flooded in late spring, with a secondary peak in summer (Scurlock, 1998). The magnitude and average duration of the spring snowmelt flood increased in the downstream direction between the San Juan Mountains and central New Mexico, as reflected in the difference between measurements near Del Norte, at Embudo, and at Otowi Bridge (Figure 3). Between central New Mexico and El Paso, the magnitude of the snow melt flood did not increase, however, because there are no other large tributaries that drain high mountain ranges with significant annual snow fall. Thus, the magnitude of the spring snowmelt flood at Otowi Bridge was nearly the same magnitude as at El Paso (Table 2).

Prior to 1915, the reach between El Paso and Presidio was a losing stream due to seepage losses, evapotranspiration, and irrigation diversions (Kelley, 1986). The entire flow was sometimes diverted at El Paso, resulting in occasional dewatering of the river downstream (Everitt, 1993). The magnitude of the 2-year recurrence flood, prior to 1915, decreased from 209 to 122 m^3/s between El Paso and the Río Conchos (Table 3). In those years when the annual peak flow at El Paso was less than 100 m^3/s, no snowmelt flood peak reached the Río Conchos. In years of greater snowmelt runoff, the magnitude of the peak flow at the Río Conchos was never more than 90% of that measured at El Paso, and typically occurred 7 to 10 days after the peak had passed El Paso. The only times when stream flows at Presidio were significantly larger than at El Paso were in the late summer and early fall when flood flows were triggered by rainfall in the downstream parts of the basin.

Table 2. Summary of hydraulic characteristics of the Rio Grande at selected gauging stations in late 1800s and early 1900s, before completion of Elephant Butte Dam.

Gauging station location and period of record	Median annual maximum mean daily discharge, in cubic meters per second	Median date of the annual maximum mean daily discharge	Mean annual discharge, in cubic meters per second[1]	Number of days whose median discharge exceeded twice the mean annual discharge
near Del Norte (1/1/1890-5/31/1890; 7/1/1890-9/30-1896; 1/1/1904-12/31/1906; 1/1/1908-9/30/1915)	107.3	June 13	27.2	60
at Embudo (1/1/1889-3/31/1904; 9/1/1912-9/30-1915)	121.7	June 5	29.5	62
at Otowi Bridge (2/1/1895-12/31/1906)	146.9	June 4	37.3	61
at El Paso (5/10/1889-6/30/1893; 1/1/1897-12/31/1897; 2/1/1898-9/30/1915)	147.0	June 18	35.1	66
above Río Conchos, near Presidio (1/23/1900-1/31/1900; 2/23/1900-2/28/1900; 3/23/1900-3/31/1914)	77.0	May 26	22.4	63
below Río Conchos, near Presidio (5/1/1900-5/31/1914)	219.0	September 6	72.1	50
at Langtry (5/1/1900 - 9/30/1913)	694	August 14	70	—

[1] computed as the mean of all days when measurements were made

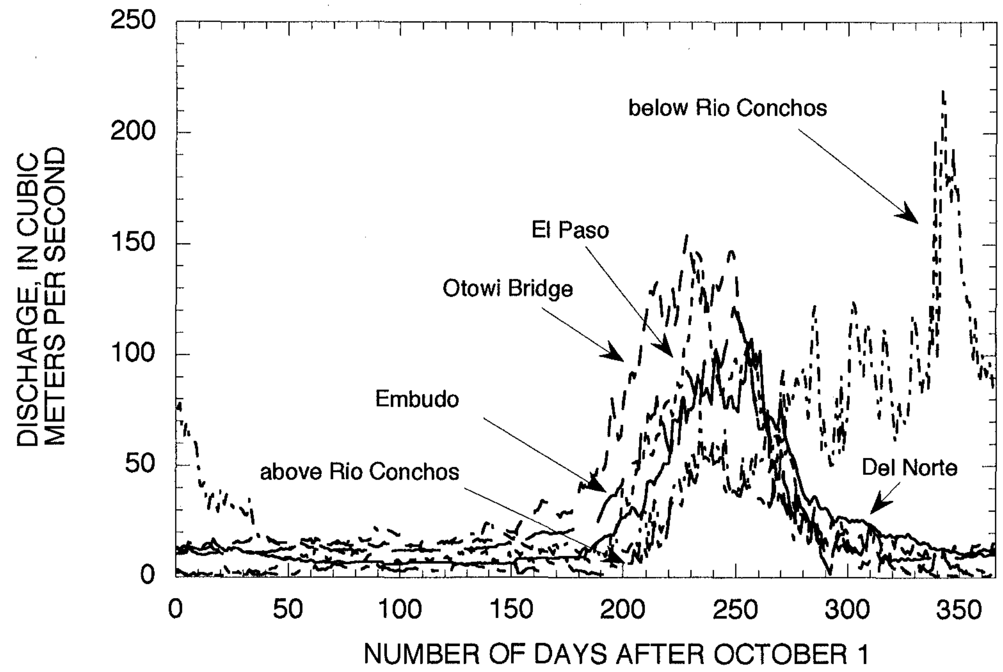


Figure 3. Graph showing median hydrographs of mean daily discharge of six gauging stations of the Rio Grande for varying periods in the late 1800s and early 1900s. See Table 2 for periods of record for each station.

Table 3. Magnitude of floods of different recurrences, upstream and downstream from the Río Conchos.

	Discharge, in cubic meters per second, of the annual maximum mean daily discharge, for the indicated period at the indicated location			
	1.25 yr	2 yr	5 yr	10 yr
1898-1916				
at El Paso	98	209	378	484
above Río Conchos, near Presidio	52	122	244	330
below Río Conchos, near Presidio	217	567	1160	1545
1916-1996				
at El Paso	32	51	100	124
above Río Conchos, near Presidio	15	34	70	99
below Río Conchos, near Presidio	126	288	661	1023

The natural hydrology of the Rio Grande changed dramatically downstream from the Río Conchos (Figure 3). The Río Conchos' hydrology is entirely determined by rainfall, which is greatest in late summer and early fall in the Sierra Madre Occidental. This watershed yields the bulk of its natural stream flow between July and the following March (Table 4). Prior to 1915, the magnitude of peak flows downstream from the Río Conchos was approximately four times what they were upstream (Table 3). During September, when the Río Conchos reached its annual maximum discharge, approximately 93% of the lower Rio Grande's total monthly flow came from the Río Conchos.

Table 4. Mean monthly discharge of the Rio Grande/Río Bravo upstream and downstream from the Río Conchos, near Presidio, 1901-1913.

Month	Mean monthly discharge above Río Conchos, in cubic meters per second	Mean monthly discharge below Río Conchos, in cubic meters per second	Percentage of mean monthly discharge of the lower Rio Grande/Río Bravo that originated in the northern branch
October	218	1002	22
November	125	592	21
December	117	537	22
January	101	298	34
February	95	362	26
March	139	297	47
April	233	291	80
May	723	795	91
June	1013	1273	80
July	543	1478	37
August	205	1828	11
September	207	2797	7

CHANNEL CHARACTERISTICS IN THE 1800S AND EARLY 1900S

The northern branch was an aggrading stream whose braided channel was constantly shifting (Graf, 1994). Large loads of sandy sediment and widely fluctuating flows caused the channel to be very wide and relatively shallow. As described in the El Paso/Juarez Valley by Major O.H. Ernst of the Army Engineer Corps in 1896 (cited by U.S. Department of State, 1903), "The size and character of the [Rio Grande] are ever varying, and its requirements as to form and dimension of bed vary equally. The river's work of altering its bed to suit the necessities of the moment is never ending." Channel change data for the part of the Rio Grande that is the international boundary demonstrate that the channel was very active and migrated rapidly across its sandy flood plain by both lateral erosion and avulsion (Mueller, 1975). Channel avulsions that were typically meander cutoffs during floods were most common in the wide alluvial valleys.

In central New Mexico, the channel was generally straight with numerous braided channels. In the El Paso area, the channel had a meandering course at flood stage, had a braided channel at low flows, and changed course frequently. There is some evidence that the Rio Grande near El Paso had a narrow sinuous channel in early historic times, suggesting that the wide shallow channel of the late 1800s was perhaps the result of a "metamorphosis" (Schumm, 1969) resulting from the flood of 1828.

In central New Mexico in 1944, the Rio Grande at base flow was described by Rittenhouse (1944, p.150) as a ..."winding, elongated sand flat, averaging about 200-300 yards in width. One or more small low-water channels meander over the sand flat, re-working the deposits in it. At high stages the entire sand flat, as well as the adjacent floodway area beyond the low banks, is under water. Between large floods the width of the sand flat is decreased by growth of cottonwoods and salt cedars. These may be removed or the entire channel shifted during high flows."

Rittenhouse (1944) also noted that the floodway was nearly 1 km wide. Lateral movements of the Rio Grande downstream from Cochiti Dam between 1918 and 1935 averaged 20 to 35 m/year (Richard, 2001).

HYDROLOGIC CHANGES IN THE BASIN

Changes to the hydrology of the Rio Grande since 1915 have been profound. Peak discharges declined upstream and downstream from Elephant Butte Dam. Changes upstream from the dam are probably due to regional climate change as well as changing patterns of irrigation diversion. These changes greatly diminished the magnitude and duration of the annual peak flood and changed the season in which these floods occur. The net effect of all changes has been to make the magnitude of the annual floods more similar throughout the northern branch (Figure 4). In fact, the average flood at Del Norte is now larger, on average, than the magnitude of floods at El Paso.

Ainsworth and Brown (1933) summarized the effect of the recently-constructed Elephant Butte Dam on the downstream water and sediment flux: "Elephant Butte Dam and Reservoir have retained the entire flow of the Rio Grande entering the reservoir during the period of operation, 1916 to date [1932]. Release of water has been entirely under control and predicated on irrigation demand [and] exceeds 2,000 second-feet for only short intervals. Practically all the silt (20,000 acre-feet annually) entering the reservoir from upper river sources has been retained above the dam."

These changes are illustrated by the median hydrograph for the period 1924 to 1940 for the reach between El Paso and Presidio (Figure 5). The well-delineated spring snowmelt peak was eliminated, and moderate flows at El Paso extended between April and September. These stable flows facilitated efficient agricultural water withdrawal in the El Paso/Juarez valley, as is evident in the difference between stream flow measured at El Paso and at Fort Quitman. These changes caused the magnitude of annual floods to be reduced by about 65 to 75% for the flows in the El Paso/Juarez valley (Table 3). In contrast, the magnitude of flood peaks downstream from the Río Conchos only decreased by between 33 and 49%, because the magnitude of flood control provided by reservoirs in the Conchos basin is not nearly as great as in the northern branch.

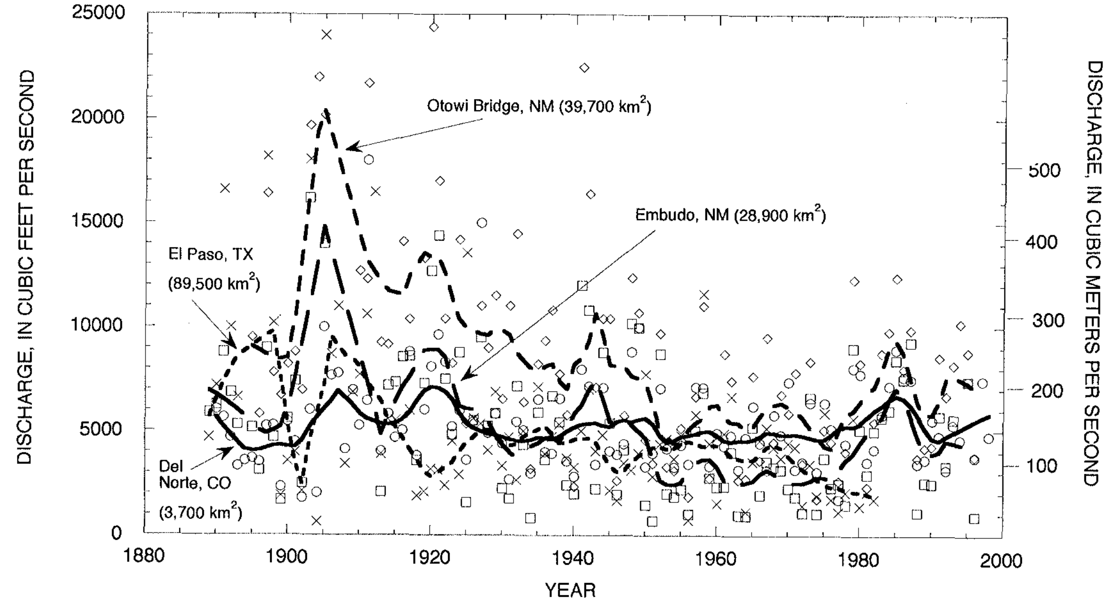


Figure 4. Graph showing the time series of annual maximum mean daily discharge at four gauging stations along the northern branch.

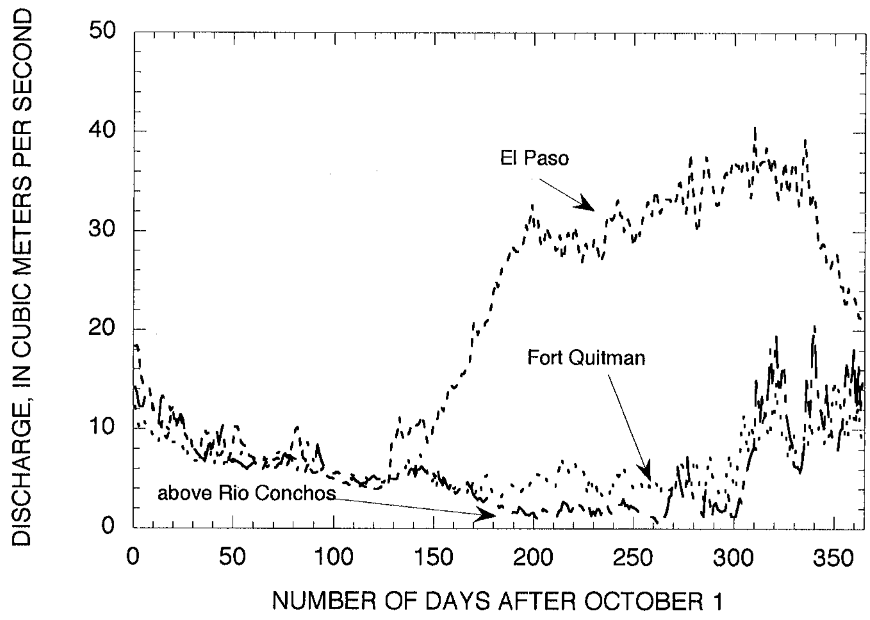


Figure 5. Graph showing median hydrographs of mean daily discharge for the Rio Grande for the period 1924-1940 at El Paso, at Fort Quitman, and above Rio Conchos, near Presidio.

Cochiti Dam affects the annual floods and the sediment input to the reach directly downstream. Cochiti Dam operations reduce those few floods exceeding 142 m^3/s, resulting in a 38% decrease in annual floods from the pre-dam (1895 to 1973) to post-dam (1974 to 1995) period at the Cochiti gage, just downstream from the dam. Further downstream at the Albuquerque gage, the impact is diminished and the annual flood was only reduced by 4% following completion of the dam. The duration of peak flows increased 60 to 130% between the same time periods (Richard, 2001). Completion of Cochiti Dam resulted in a 99% reduction in sediment concentration flowing into the channel downstream. Upstream from the dam, at the Otowi Bridge, the suspended-sediment concentration also declined around this time, and thus some aspect of reduced sediment concentrations may be due to regional climate and land use change. Suspended-sediment transport increases downstream from the dam due to re-supply of fine sediment from tributaries and/or erosion of the bed and banks. As a result, the post-dam reduction in annual mean suspended sediment concentration at the Albuquerque gage is 78% (Richard, 2001).

RESULTING CHANNEL CHANGES

Today, the northern branch between Cochiti Dam and Presidio can be divided into two long segments – one segment affected by the existence and operations of Cochiti Dam and the other affected by the existence and operations of Elephant Butte and Caballo dams. In the two segments, the reach nearest the dam has experienced bed degradation and coarsening of bed material. Further downstream in each segment, the channel has aggraded in reaches where the combined influx of sediment from tributaries exceeds the diminished transport capacity of the river. The degrading reach downstream from Cochiti Dam probably extends to San Acacia, although smaller diversion dams at Angostura, Isleta, and San Acacia complicate this longitudinal pattern. The aggrading reach extends from there to the head of Elephant Butte Reservoir. The degrading reach downstream from Caballo Dam once extended to the Mesilla Valley, but channelization has obliterated this evidence. The channel has significantly aggraded downstream from El Paso, but a natural channel only exists downstream from Fort

Quitman. Within each segment, reaches have received different cultural treatments, in terms of direct manipulation to the channel and floodplain (Table 5).

The description of channel change between Cochiti Dam and Amistad Reservoir is based on an unusually comprehensive set of geomorphic data. The combination of severe flooding and sedimentation between Cochiti and Elephante Butte, along with irrigation needs in the middle Rio Grande valley in the early 1900s prompted state and federal agencies to begin intensive surveys of the river. These surveys include cross-section surveys beginning in 1918, bed material sampling beginning in the 1930s, suspended sediment sampling beginning in the 1940s, and aerial photography (Leon et al., 1999). Changes along the international boundary are monitored by the International Boundary and Water Commission.

Table 5. Summary of cultural impacts to the Rio Grande between Cochiti Dam and Amistad Reservoir.

Reach		Flood Regime		Cultural Treatment		
From	To	Pre-1915	Post-1915	Channelization	Regulation	Depletion
Cochiti	Elephant Butte	spring	spring	moderate??	moderate	minor
Caballo	El Paso	spring	summer	moderate	extreme	moderate
El Paso	Fort Quitman	spring	summer	extreme	extreme	extreme
Fort Quitman	Candelaria	spring	summer	minor	extreme	extreme
Candelaria	Presidio	spring	summer	moderate?	extreme	extreme
Presidio	Amistad Reservoir	summer	summer	none	moderate	moderate

CHANNEL CHANGES DOWNSTREAM FROM ELEPHANT BUTTE AND CABALLO DAMS

Completion of Elephant Butte Dam caused the channel to degrade immediately downstream from the dam. Further downstream, the channel began to shrink in size in the El Paso/Juarez valley, because the low-gradient channel could not transport this delivered load, nor the load sluiced to the channel from irrigation channels or delivered naturally from ephemeral tributaries. Ainsworth and Brown (1933) reported that: "Silt carried in suspension past El Paso now varies from 0.03 percent to 1.5 percent by volume, depending upon the ratio of arroyo runoff to reservoir releases. But by far the greater part of the material transported is sand traveling probably as bottom load. This is either scoured from the riverbed or from the arroyo fans which are annually replenished by run-off from the summer rains. The controlled flow in the river is successively depleted for irrigation use at the various diversion points along its course, at each of which, through operation of skimming weirs and sand sluiceways, a great part of the sand is returned to the riverbed. The ordinary flow of the river by El Paso is not capable of transporting the load of sand and silt annually brought down the river from above."

"Peak flows at El Paso since Elephant Butte Dam, as a result of the above factors, are of annual occurrence, and while usually under 4,000 second-feet, have amounted to 13,500 second-feet. The peak of these floods is sharp, lasting but a few hours so that the total acre-footage passed is low. The short duration of these summer floods precludes, as to the valley below El Paso, any lasting scouring action or long distance transportation of the accumulated deposits. Their action is more to carry the sand scoured from the bed over banks onto the flood plain, which is thus being constantly elevated. A general lowering of the river bed above El Paso has taken place [while] a general filling of the riverbed below El Paso has taken place. Narrowing of the normal channel has progressively occurred both above and below El Paso. This effect is most marked below El Paso where the normal channel has only about one third its former width."

"River gradients have been but little disturbed except where cut-offs have been made and in the immediate reaches above diversion dams or above plugs (of sediment) deposited by side flow and except for the reach of river immediately below the International Dam where filling has resulted in an increase in gradient from 2.45 feet per mile in 1917 to 3.00 feet per mile in 1932. However, decreasing gradients due to increasing river lengths are apparent below El Paso where the natural length has been undisturbed by cut-offs."

"River length above El Paso has apparently been slightly shortened by natural processes and reduced about five miles by artificial cut-offs. River length below El Paso has been lengthened by nearly 20 percent (compared to 1907) and by about 4 percent (compared to 1917) in those reaches where neither cut-offs have been made or avulsions occurred. River length above and below El Paso, when compared to valley axial length, has a ratio of 1.21:1 and 1.91:1, respectively."

"The processes of the adjustment of the bed of the river to the new conditions of flow are not complete ...."

Channel shrinking on the Rio Grande provided the first clear evidence that large main stem dams in the western United States do not necessarily provide downstream flood control, and under certain conditions may actually increase flood risk due to diminished channel capacity. It spawned a short-lived discussion in the engineering literature of the 1920s and 1930s regarding the long-term effect of structural methods of flood control (Lawson, 1925; Stevens, 1938). The problem, from the point of view of water supply and flood control, was summarized in the Joint Report of the Consulting Engineers, International Boundary Commission, on rectification of the Rio Grande (IBWC, 1933): "Notwithstanding the fact that the present total amount of sediment annually carried through this valley by the Rio Grande is only a very small percentage of that carried previous to the construction of the Elephant Butte Dam, the absence of the former large scouring floods has resulted in the silting up of the river channel to a point where rainfall discharges from arroyos entering the river between Elephant Butte and El Paso-Juarez menace the improved and developed properties of both cities and valley lands. Only large floods of destructive proportions are capable of eroding accumulations of sediment as they now occur in the meandering channel."

This report and the subsequent analysis of Ainsworth and Brown (1933) provided justification for straightening and channelizing the river from Elephant Butte to Fort Quitman. The channelization was begun about 1933 and essentially completed in 1938. This reach of river is now artificially maintained as a water delivery and drainage canal.

Studying the remaining unchannelized reach between Fort Quitman and Presidio, Everitt (1993) concluded that the physical changes in the channel represented a complex chain of responses driven by deposition of excess sediment which the depleted river was no longer able to transport. He proposed a three-stage model for channel evolution. This model provides a conceptual basis for evaluating the relationship among the interdependent variables of declining stream flow, decreased flood magnitude and duration, floodplain aggradation, and channel capacity.

Everitt (1993) termed changes in channel width, channel depth, and channel cross-section area as "first-order responses" which began immediately after the flow regime changed, as excess sediment was deposited within the abandoned, oversized channel. Once channel capacity was reduced, over-bank flow resumed. These "second-order responses" included meander cutting, changes in the relationship between the main channel and its tributaries, and readjustment of channel gradient.

Deposition of sediment within the pre-dam channel of the Rio Grande occurred between 1915 and 1925 in the upstream end of the El Paso/Juarez valley (Ainsworth and Brown, 1933). The channel shrank in cross-sectional area, and overbank flooding did not occur during this time. Downstream from Fort Quitman, a similar pattern of infilling without overbank flooding occurred between 1915 and 1932. Photographs of the river taken during the U.S. Geological Survey hydrographic survey of 1901 depict a broad, shallow, sand-bedded channel downstream from Fort Quitman. Maps of the pre-dam river show a channel about 100 m wide. Aerial photographs taken in 1928 show that the channel had narrowed to about 30 m. Today, some of this old channel survives as oxbows that are lined with very old cottonwoods.

Beginning in 1925 near El Paso/Juarez and beginning in 1932 downstream from Fort Quitman, the channel's flood capacity had sufficiently decreased such that the lower magnitude floods of this period again began to overtop its banks, depositing fine sediment across the valley floor (Figure 7). Floodplain inundation is a necessary process to cause meander cutoffs, and cutoffs became a renewed geomorphic process that had not occurred since 1915. Cutoffs occurred in each year in which flood discharges were large in relation to the shrunken channel.

The process of channel shrinkage was reversed in 1941 and 1942 when there were unusually large releases from Elephant Butte reservoir. Losses were not great during these floods and the peak discharge at Presidio, upstream from the Río Conchos, was 145 m^3/s, which would have been about a 3-year recurrence flood prior to 1915. The high flows reestablished a larger channel cross-section that was narrower and deeper than the pre-dam channel (Figure 7). These changes occurred by erosion of the channel bed and by deposition of new floodplain sediments.

Channel infilling resumed after 1943 and continued downstream from Fort Quitman until 1963 (Figure 7). After 1963, sufficient aggradation had occurred that floodplain inundation and meander cutoffs again began to occur. In 1970, the Rio Grande channel was between 10 and 15 m wide (Everitt, 1993). The channel of the Rio Grande between Fort Quitman and Presidio is now about 90% smaller than the channel that existed in 1900.

Thus, the Rio Grande channel decreased in size by aggradation of the stream bed and deposition of bars inset within the former active channel and by floodplain deposition. Everitt (1993) concluded that the post-1970 channel of the Rio Grande was approaching a balance between discharge and channel capacity. Thus, with the resumption of over bank flow the valley floor had resumed its function of storage of floodwater and sediment. Thus, deposition of sediment in the Rio Grande valley since about 1970 has occurred by concurrent deposition in the channel and on the floodplain such that the relationship between the two geomorphic features remains the same, and the geomorphic functionality of the river is relatively unchanged.

The contrast between the channelized reach between El Paso and Fort Quitman, and the natural reach from Fort Quitman and Candelaria, illustrates the consequences of different cultural treatments. Both reaches were initially similar in physical geometry and hydrology, and both experienced similar changes in flow regime following construction of Elephant Butte Dam. The channelized reach resembles a drainage ditch, dewatered much of the year, separated from its flood plain by steep banks, and with floodplain vegetation artificially main-

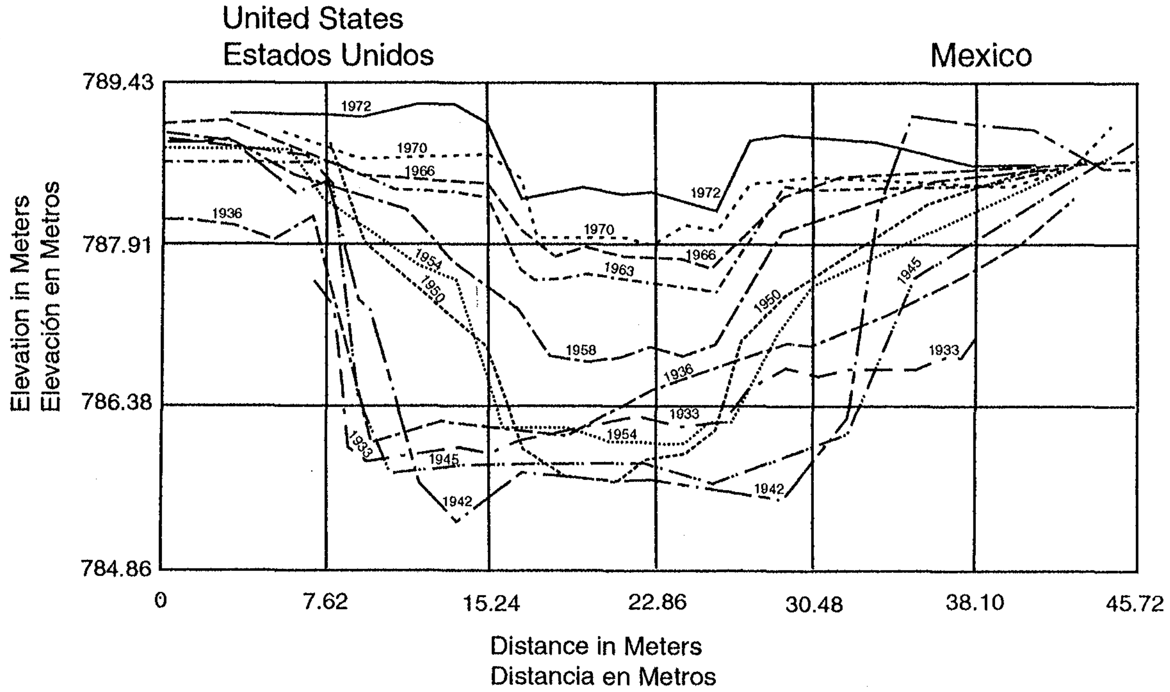


Figure 6. Graph showing composite cross sections of the Rio Grande channel at the gauging station above Rio Conchos, near Presidio, 1933-1974 (from Everitt, 1993, fig. 3).

tained by mowing. Beyond the levees, what remains of the cottonwood gallery forest is cut off from the river, its seeds falling on barren ground. Former tributaries have been cut off by erosion-control dams, isolating the river from its watershed. The riverine landscape has lost the physical continuity that once provided migration routes for riparian plants and animals, and the dynamic nature that once provided cycling and storage of water and nutrients.

Downstream from Fort Quitman, although severely depleted in stream flow, the river continues to be a functioning part of the landscape. Channel dimensions in some reaches have adjusted to the altered discharge so that a smaller river flows in a smaller channel in a relatively broader flood plain. As in pre-dam times, the river continues to meander in some places forming oxbows and in others braiding and forming islands, maintaining the topographic irregularities that provide habitat diversity. The mosaic of landscape elements necessary for the foundation of a healthy riparian ecosystem is still present. Brushy banks with fallen trunks provide shaded scour holes for fish. Natural levees pond flood water beyond the channel, allowing it to percolate slowly back to the river, maintaining the shallow alluvial ground-water system and prolonging base flow. Broad overflow lands spread and filter water during high stages and flush accumulated salt from the soil. Here the river landscape retains both its longitudinal and lateral continuity, although there have been profound changes in the vegetation.

COCHITI TO ELEPHANT BUTTE

Changes in the Rio Grande between Cochiti and Bernalillo are similar to the pattern of bed degradation and narrowing that occurred soon after completion of Elephant Butte Dam. Richard's (2001) study of adjustments of the Rio Grande between Cochiti and Bernalillo demonstrated that continued lateral adjustments, includ-

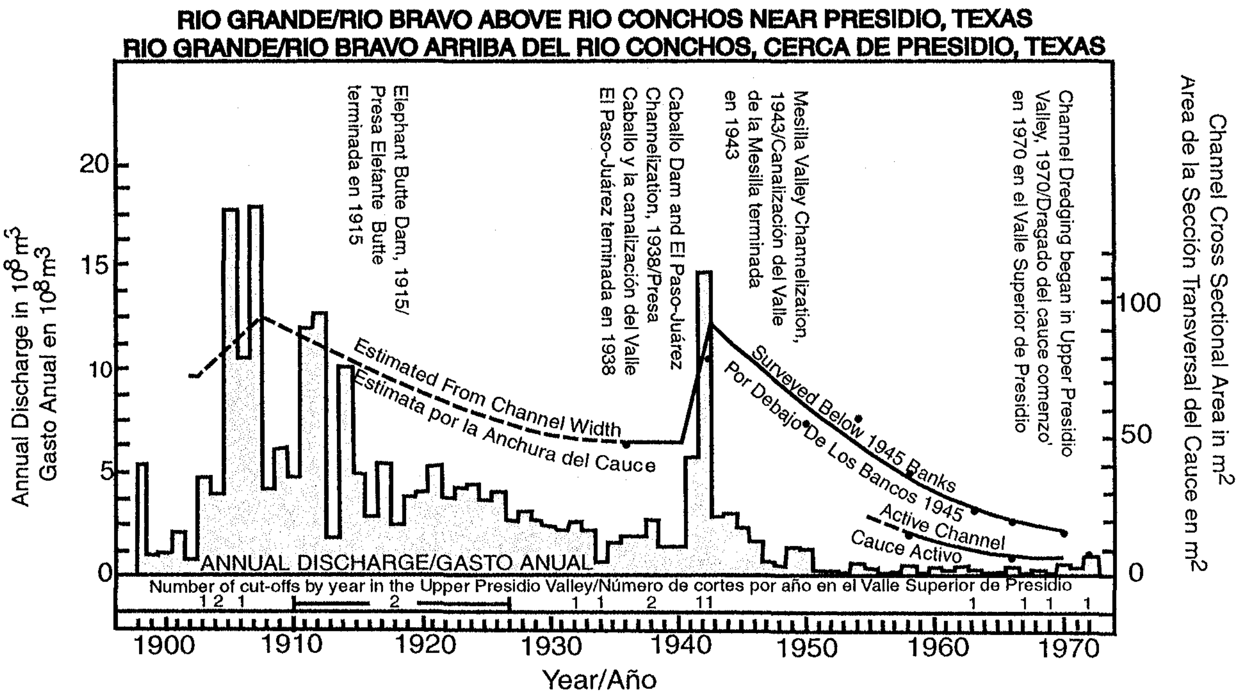


Figure 7. Graph showing time series of change in annual discharge and cross section at the gauging station above Rio Conchos, near Presidio, 1933-1974 (from Everitt, 1993, fig. 2).

ing narrowing and decreased lateral migration rates, occurred between 1918 and 1992. More rapid vertical adjustments occurred following construction of the dam in 1973. Prior to dam construction, the bed of the channel was primarily sand. The sandy bed of the channel responded to the temporal variability in sediment inputs by alternating aggradation and degradation; the net sum was gradual aggradation of the bed. Bed degradation began after Cochiti Dam was completed and up to 1.9 m of bed erosion occurred between 1972 and 1998. Following dam construction, the bed material between Cochiti and Bernalillo coarsened to gravel and cobbles (Richard, 2001).

Measurements from historic maps and aerial photographs indicate that as the peak discharges began to decrease (ca. 1930s) due to natural and anthropogenic factors the channel responded by narrowing, simplifying and reducing its rate of lateral migration (Figure 8). The width of the Rio Grande between Cochiti and Bernalillo decreased 60% prior to dam construction and by 1992 the channel was 70% narrower than in 1918. Also between 1918 and 1992 the channel planform shifted from a multi-thread braided configuration toward a single-thread pattern as the number and size of mid-channel bars and islands decreased (Figure 9). Following dam construction, a meandering pattern became more pronounced as the sinuosity of the channel downstream from Cochiti increased slightly (Richard, 2001).

Richard (2001) concluded that attempts to "stabilize" the Cochiti reach of the Rio Grande through flood control, sediment detention, channelization, and bank stabilization succeeded in reducing the dynamism in both the inputs to the reach and in the responding form of the channel. Average lateral movements of the channel decreased from 27 m/year in 1918 to 5 m/year in 1992, and the active channel width has remained less than 100 m since 1985. Incision of the channel bed following construction of the dam disconnected the channel from the floodplain. The resulting narrow and deep configuration of the channel and reduced peak flows creates a situation in which even the highest flows no longer achieve bankfull conditions (Richard, 2001).

DISCUSSION

IMPLICATIONS OF HYDROLOGIC AND GEOMORPHIC HISTORY FOR RIVER RESTORATION OR REHABILITATION

We have shown that the physical attributes of the Rio Grande—its hydrology, sediment load, channel dimensions, and temporal variability of channel location – are much different than they were a century ago. Some segments are still evolving in response to past alteration in flood regime, depletion of flow, and deposition of sediment in reservoirs.

The aquatic and riparian ecosystems are also much different than they were a century ago. Ecosystem change is driven by the following variables:

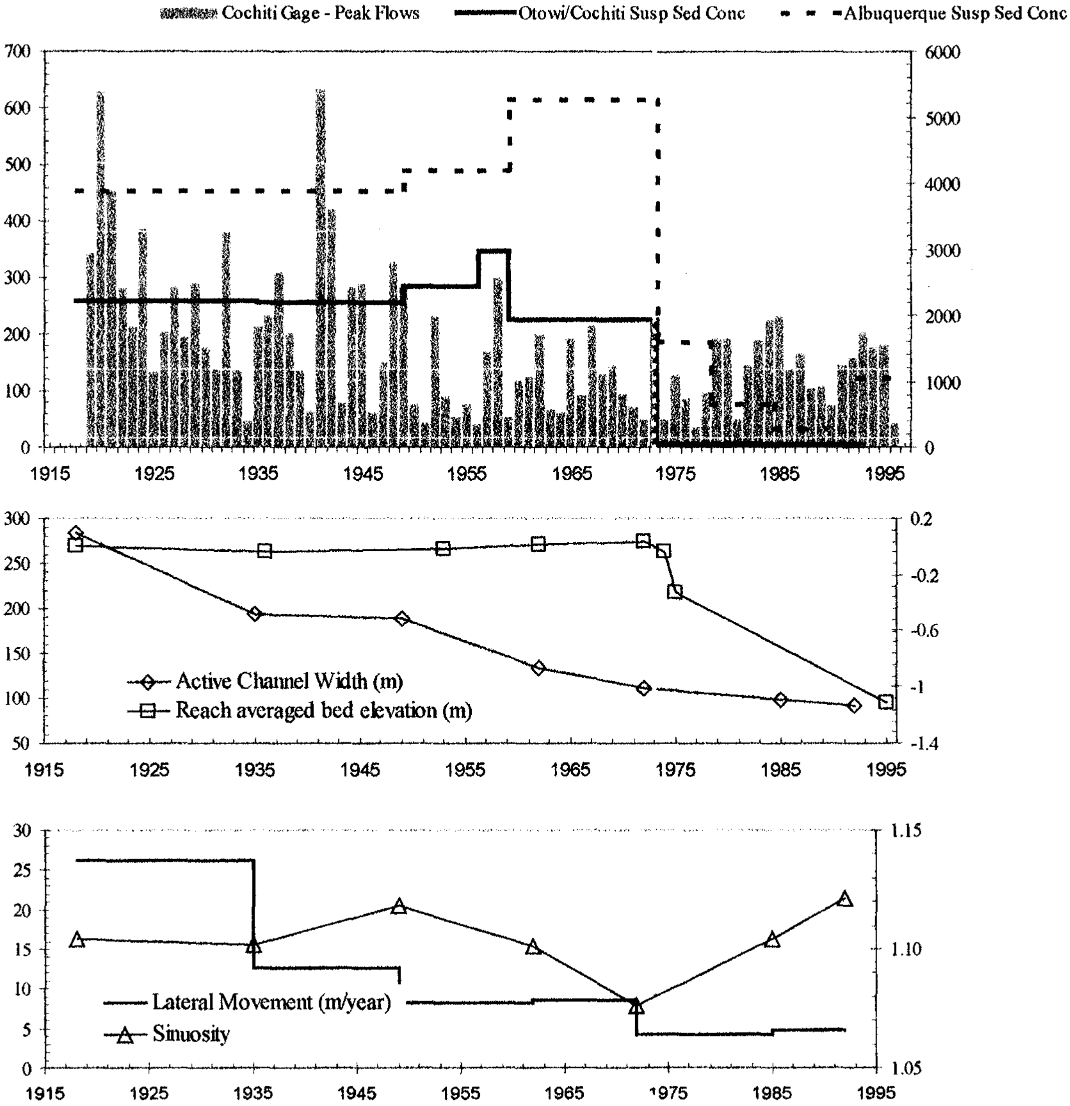
1) Change in climate that affects the runoff and sediment flux.

2) Change in hydrologic and sediment regime caused by human activities.

3) Changes in the physical structure of the channel and floodplain. These changes are caused by changes in the flux of water and sediment and by direct manipulation of the channel or floodplain. The fundamental attributes of physical structure are the cross-sectional form of the channel, the characteristics of the bed material and how it is organized, channel planform, channel gradient, and the relationship between the channel and its alluvial valley. These changes not only affect the distribution of aquatic habitats and the exchange rate of sediment between channel and alluvial valley but also the characteristics of nutrient spiraling.

4) Introduction of exotic species. In addition to many naturalizing herbs and grasses, there are 3 woody exotics that are expanding their range at the expense of native vegetation along the Rio Grande: Russian olive (*Eleagnus angustifolia* L.) in the upstream part of the northern branch, salt cedar in the southern part of the northern branch and the upstream part of the lower Rio Grande, and giant reed (*Arundo donax*) downstream from Presidio.

5) The internally-driven dynamics of ecosystems that cause some species to replace others over time.



Cochiti Dam
1973

Figure 8. Summary of changes in the Rio Grande between Cochiti Dam and Bernalillo from 1918 to 1992.

Of these input variables, climate change is beyond the control of Rio Grande managers. Eradication of non-native species invasions and vegetation manipulation that alters the trajectory of ecosystem change are extremely difficult, although large-scale eradication of salt cedar has been conducted in parts of the Pecos River alluvial valley.

It is only by manipulating the runoff regime, sediment regime, or physically altering the channel or floodplain that we can alter the balance among competing species in a functioning ecosystem. We know we can do this, because we have already performed experiments on the Rio Grande. A hundred years of data on the 6 reaches of Table 5 provide case studies of how local riparian communities respond to different kinds of treatment under different local circumstances. Elsewhere, stream flow and sediment fluxes are being altered by dam reoperations in order to alter down stream ecosystems.

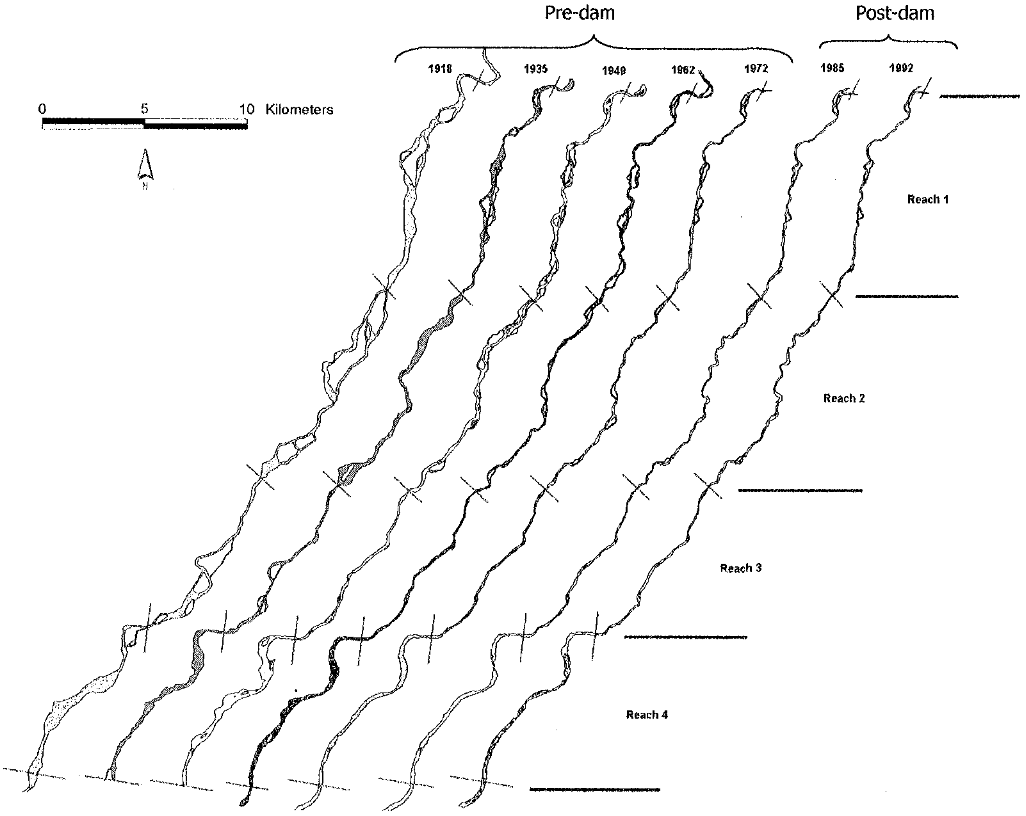


Figure 9. Planform maps of the active channel of the Cochiti reach for 1918 through 1992.

OTHER GOALS FOR ENVIRONMENTAL MANAGEMENT

Environmental management of the Rio Grande must be grounded in establishment of a set of well-defined goals for the future trajectory of ecosystem change on each segment. Ecosystem restoration is defined as "the return of an ecosystem to a close approximation of its condition prior to disturbance" (National Research Council, 1992). There also are other possible goals for aquatic ecosystems, including reclamation, rehabilitation, mitigation, and creation (National Research Council, 1992). *Reclamation* is the process of adapting a wild or natural resource to serve a utilitarian human purpose. Thus, this term is reserved for activities such as converting native floodplain ecosystems to agricultural uses. *Rehabilitation* is a term used primarily to indicate putting a natural resource back into good condition or working order. *Mitigation* is typically defined as alleviating any or all detrimental effects arising from a specific human activity. *Creation* is the bringing into being of a new ecosystem that previously did not exist at the site. Environmental management goals might include any of those listed above. Choice of goals, on a segment by segment basis, is an effort in policy development, will inevitably be based on dialogue among river stakeholders, and is necessarily political.

Disturbances to the hydrologic regime of the Rio Grande began hundreds of years ago and are significant. Restoration of the Rio Grande's northern branch to its condition in 1900 would require dam decommissioning and the abandonment of most irrigated agriculture in southern Colorado, New Mexico, the El Paso/Juarez valley, and the Presidio valley. Restoration would also require removal of levees, rehabilitation of channelized sections, and relocation of large numbers of people from the historic floodplain of the rivers, especially in El Paso and Cuidad Juarez. Political consensus to undertake such a comprehensive program of river restoration probably does not exist in either the United States or Mexico. Thus, it is essentially impossible to restore most of the river.

Goals for the Rio Grande might include (1) rehabilitation to some post-1915 condition, although the channel was not in equilibrium with its floodplain for most of this time, (2) rehabilitation so that the channel and alluvial valley have a broader suite of ecological processes and attributes similar to the pre-disturbance river, (3) mitigation by maintenance of a new ecosystem, with or without salt cedar, that is adjusted to a specified range of flood flows and annual flows, (4) mitigation to the level of ecosystem function necessary to recover endangered species, or (5) acceptance of the riverine ecosystem as it is today. The identification of the appropriate goal depends on a precise identification of the natural and human values that would be improved and degraded if the present ecosystem were changed.

There is probably no single environmental management goal that is appropriate for all of the Rio Grande. Each goal described above is associated with its own economic cost, and achievement of political consensus on any environmental management goal is difficult to achieve. Knowledge of the magnitude of twentieth century environmental change does not necessarily mean the trajectory towards restoration will follow the same path and the trajectory of historical change. Where channels have significantly narrowed, become disconnected from their floodplains, and overgrown with salt cedar, the question remains whether reintroducing more natural water and sediment fluxes will immediately reverse undesired historical changes. Restoration science is not yet able to predict these trajectories of system recovery.

In the face of such uncertainty, pursuing uniform basin-wide rehabilitation goals is essentially impossible. Is it better to ask where in the basin can undesired historical changes be efficiently reversed? Where in the basin will the native riverine ecosystem respond most favorably to reversal of historical changes in the physical environment? Where can the historical changes of water and sediment flux be feasibly reversed and at what political cost? Where is the greatest need for rehabilitation? Answers to each of these questions can only be provided by considering what is feasible and possible in each segment of the river. Only then can one examine how much water is available for redistribution to environmental objectives and develop an allocation system that recognizes the needs of the natural riverine ecosystem and the physical template within which it has developed.

CONCLUSION

The extent of changes to the water and sediment flux are so great, and the extent of changes to the physical system of the channel and floodplain are so extensive, that comprehensive restoration of the Rio Grande is impossible. Priorities must be established wherein different environmental management goals are established for different segments of the river system. Establishment of these priorities is inevitably a political process, wherein the role of the scientific community is to present a clear picture of the magnitude of transformation of the present riverine ecosystem from its pre-disturbance condition and the activities necessary to rehabilitate the ecosystem to varying degrees or to reverse undesired changes in the physical or ecological system.

ACKNOWLEDGEMENTS

Critical review of a draft manuscript was provided by Kevin M. Urbanczyk and an anonymous reviewer. Data from the National Inventory of Dams was graciously provided by W. L. Graf.

LITERATURE CITED

Ainsworth, C. M. and F. P. Brown. 1933. Report on the changes in regimen of the Rio Grande in the valleys below since the construction of Elephant Butte Dam, 1917-1932. Unpublished report of the United States Section, International Boundary and Water Commission, El Paso, Texas.

Aulbach, L. F. and J. Butler. 1998. The lower canyons of the Rio Grande. Wilderness Area Map Service, Houston, Texas, 94 pp.

Aulbach, L. F. and L. C. Gorski. 2000. The upper canyons of the Rio Grande. Wilderness Area Map Service, Houston, Texas, 93 pp.

Bullard, K. L. and W. L. Lane. 1993. Middle Rio Grande peak flow frequency study. U.S. Bureau of Reclamation, Albuquerque, New Mexico.

Dewey, J. D., F. E. Roybal, and D. E. Funderburg. 1979. Hydrologic data on channel adjustments 1970 to 1975, on the Rio Grande downstream from Cochiti Dam, New Mexico before and after closure. U. S. Geological Survey Water Resources Investigations 79-70, Albuquerque, New Mexico.

Dortignac, E. J. 1956. Watershed resources and problems of the upper Rio Grande basin. USDA Rocky Mountain Forest and Range Experiment Station report, Fort Collins, Colorado, 107 pp.

Emory, W. H. 1857. Report on the United States and Mexican boundary survey, made under the direction of the Secretary of the Interior. 34th Congress, 1st Session, Senate Exec. Doc. No 106.

Everitt, B. 1993. Channel response to declining flow on the Rio Grande between Ft. Quitman and Presidio, Texas. Geomorphology, 6:225-242.

Graf, W. L. 1994. Plutonium and the Rio Grande – environmental change and contamination in the nuclear age. Oxford University Press, New York, New York.

Grams, P.E. and Schmidt, J.C. 2002. Streamflow regulation and multi-level floodplain formation: channel narrowing on the aggrading Green River in the eastern Uinta Mountains, Colorado and Utah. Geomorphology, 44:337-360.

IBWC. 1933. Joint report of consulting engineers. *in* Rectification of the Rio Grande: Convention between the United States of America and the United States of Mexico, U.S. Department of State, Mexico City.

Kelley, P. 1986. River of lost dreams: navigation on the Rio Grande. University of Nebraska Press, Lincoln.

Lawson, L. M. 1925. Effects of Rio Grande storage on river erosion and deposition. Engineering News-Record, 95 (10):372-374.

Leon, C., G. Richard, T. Bauer, and P. Julien. 1999. Middle Rio Grande, Cochiti to Bernalillo bridge, hydraulic geometry, discharge and sediment data base and report. Colorado State University, Fort Collins.

Meade, R. H., T. R. Yuzyk, and T. J. Day. 1990. Movement and storage of sediment in rivers of the United States and Canada. Pp. 255-280, *in* Surface Water Hydrology (M. G. Wolman and H. C. Riggs, eds.), The Geology of North America, vol. O-1, The Geological Society of America, Boulder, Colorado.

Moles, M. C., Jr., C. S. Crawford, L. M. Ellis, H. M. Valett, and C. N. Dahm. 1998. Managed flooding for riparian ecosystem restoration. Bioscience 48(9):.

Mueller, J. E. 1975. Restless River. Texas Western Press, El Paso, 155 pp.

National Research Council. 1992. Restoration of aquatic ecosystems. National Academy Press, Washington, D.C., 552 pp.

Richard, G. A. 2001. Quantification and prediction of lateral channel adjustment downstream from Cochiti Dam, Rio Grande, NM. PhD dissertation, Colorado State University, Fort Collins.

Rittenhouse, G. 1944. Sources of modern sands in the middle Rio Grande valley, New Mexico. Journal of Geology, 52:145-183.

Sanchez, V. and D. Baird. 1997. River channel changes downstream from Cochiti Dam, middle Rio Grande, New Mexico. In Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision. University of Mississippi, Oxford.

Schumm, S. A. 1969. River Metamorphosis. Journal of the Hydraulics Division, 95:255-273.

Scurlock, D. 1998. From the Rio to the Sierra: an environmental history of the middle Rio Grande basin. USDA Forest Service General Technical Report RMRS-GTR-5, 440 pp.

Sorenson, E. F. and D. Linford. 1967. Rio Grande basin – settlement, development, and water use. Pp. 143-168, *in* Water Resources of New Mexico: Occurrence, Development, and Use. New Mexico State Engineer, State Planning Office, Santa Fe.

Stevens, J. C. 1938. The effect of silt removal and flow regulation on the regimen of the Rio Grande and Colorado Rivers. American Geophysical Union Transactions, 653-656.

Stotz, N. G. 2000. Historic reconstruction of the ecology of the Rio Grande/Rio Bravo channel and floodplain in the Chihuahuan Desert: Desert Scribes, Las Cruces, report prepared for Chihuahuan Desert Program, World Wildlife Fund, 158 pp.

Thomas, H. E. and others. 1963. Effects of drought in the Rio Grande basin. U.S. Geological Survey Professional Paper 372-D, 59 pp.

U. S. Army Corps of Engineers. 1978. Cochiti Lake, Rio Grande basin, New Mexico, water control manual, appendix C to Rio Grande basin master water control manual. Albuquerque, New Mexico.

U. S. Army Corps of Engineers. 1996. Water control infrastructure: national inventory of dams [CD-ROM]. Federal Emergency Management Agency, Washington, D. C.

U.S. Department of State. 1903. Proceedings of the International Boundary Commission, United States and Mexico, equable distribution of the waters of the Rio Grande.

Addresses of Authors:

JOHN C. SCHMIDT

Department of Aquatic, Watershed, and Earth Resources
Utah State University
Logan, Utah 84322-5210
e-mail: jschmidt@cc.usu.edu

BENJAMIN L. EVERITT

Utah Division of Water Resources
Salt Lake City, Utah
e-mail: beneveritt@utah.gov

GIGI A. RICHARD

Department of Physical and Environmental Sciences
Mesa State College
Grand Junction, CO 81501
e-mail: grichard@mesastate.edu