1. INTRODUCTION

1.1. Background

The Middle Rio Grande, as defined in this report, is that part of the Rio Grande in New Mexico that extends from Cochiti Dam to Elephant Butte Reservoir, a distance of about 165 miles (**Figure 1.1**). The Rio Grande valley has been a home to the Pueblo people, Spanish colonizers, and Americans (Horgan, 1954; Crawford et al., 1993). The valley has a complex geomorphic and geologic history (Belcher, 1975) and hydrologic conditions are unusual (Graf, 1994). For example, discharge decreases as the river flows from areas of higher to lower precipitation (**Figure 1.2**). However, contributions from Rio Puerco and Rio Salado increase flood peaks between Albuquerque and San Marcial (**Figure 1.3**). Both suspended load and bed load are increased dramatically by contributions from the Rio Puerco and Rio Salado (**Figures 1.4 and 1.5**).

Therefore, the Rio Grande would not be expected to conform to the hydraulic geometry relations of perennial rivers elsewhere, and the hydrologic and sediment load variability has produced a braided river that varies in dimensions, pattern, and dynamics in a downstream direction. This variability is compounded by major river control schemes and irrigation dams and diversions.

1.2. Project Objectives

The general objectives of this study were to: (1) evaluate the historic and present characteristics of the river, (2) identify the natural and human-induced factors that control river characteristics, and (3) evaluate opinions that have been expressed by the USBR and others regarding the narrowing and incision of the river over the past century.

Specific objectives of the investigation included:

1. Identification of geomorphic and sediment data that will be necessary to develop a predictive tool(s) that relates river flow and physical characteristics of the river.

2. Assembly and evaluation of the existing data, and review and analysis of studies conducted by others.

3. Evaluation of the geomorphology of the river immediately downstream of each of the diversion dams (Angostura, Isleta, and San Acacia) within the project Reach to provide a basis for evaluating proposed restoration projects by the U.S. Bureau of Reclamation (USBR).

4. Qualitative evaluation of how currently proposed habitat restoration activities, if implemented, would affect river efficiency (i.e., ability to convey flows downstream with minimal losses through seepage, evaporation and evapotranspiration).

5. Qualitative evaluation of where natural overbank flooding was possible immediately after closure of Cochiti Dam in 1973, and under present conditions.

6. Preliminary identification of where it might be possible to modify the floodplain to allow short-term inundation of the floodplain.

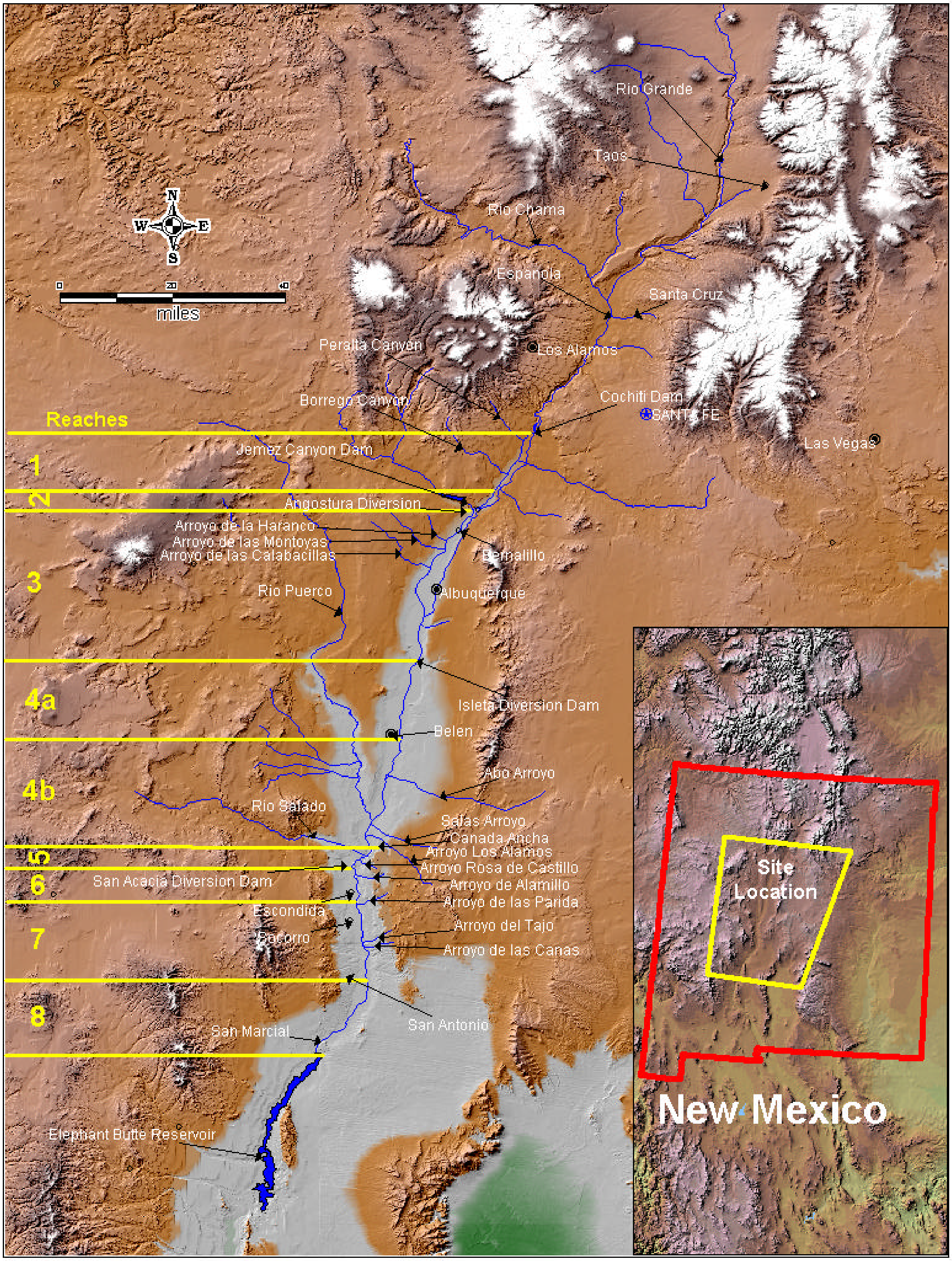


Figure 1.1. Map of the project Reach of the Rio Grande showing the locations of features identified and discussed in the report, as well as the reach boundaries identified by MEI.

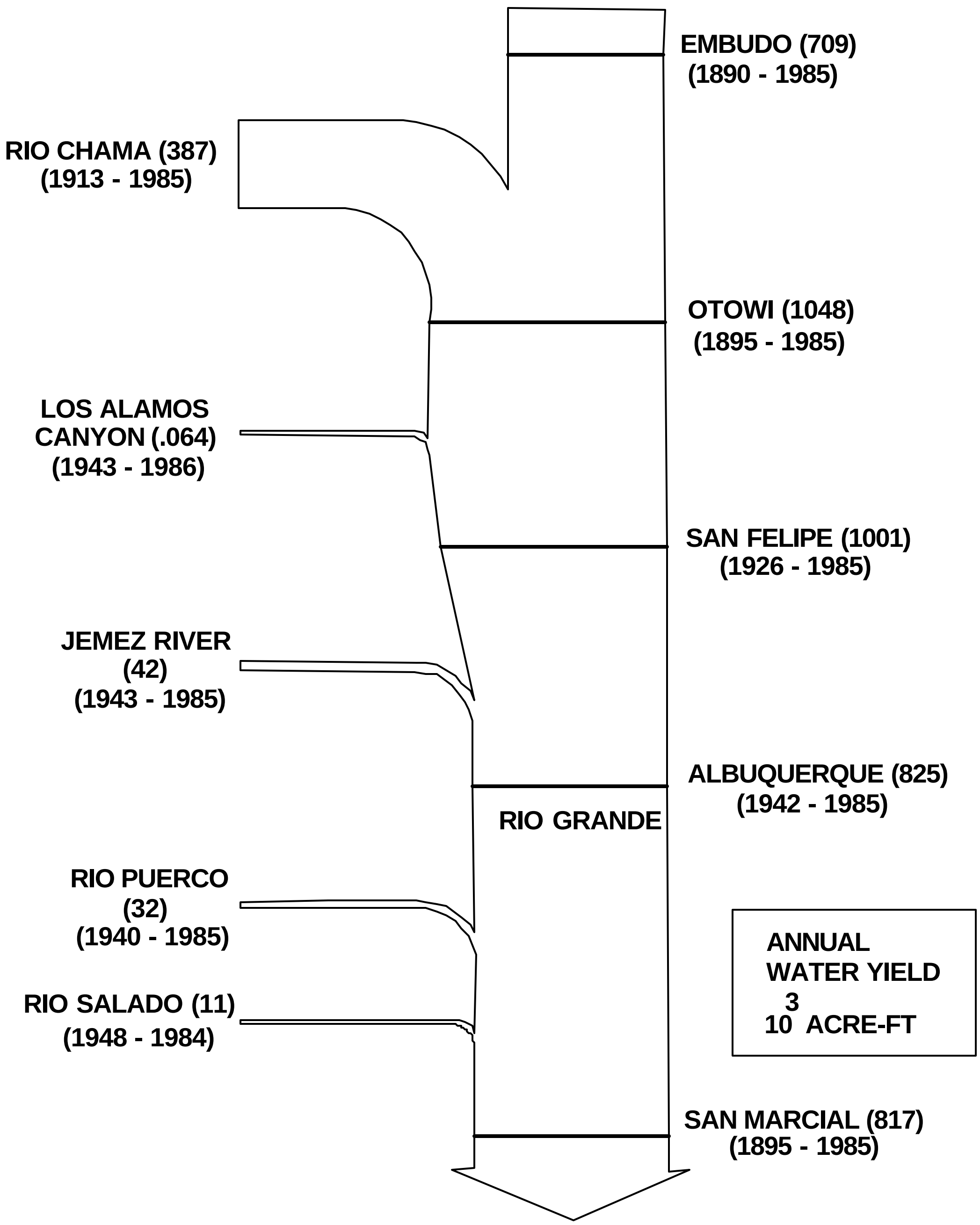


Figure 1.2. Flow diagram for the annual water yield budget of the Northern Rio Grande (Graf, 1994). The indicated values are averages based on the indicated periods of record for each of the gages.

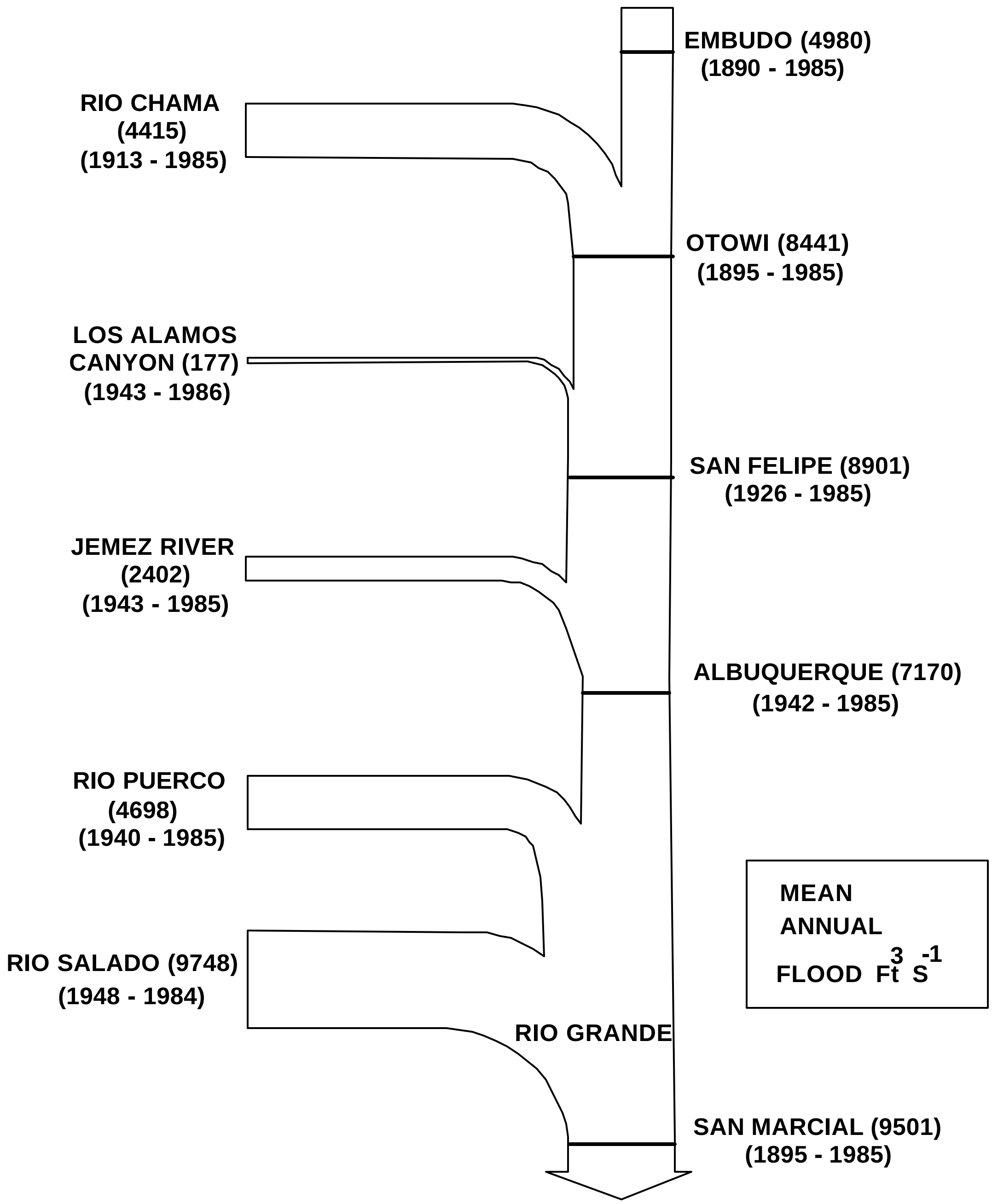


Figure 1.3. Flow diagram for the annual maximum flood series of the Northern Rio Grande (Graf, 1994). The indicated values are averages based on the indicated periods of record for each of the gages.

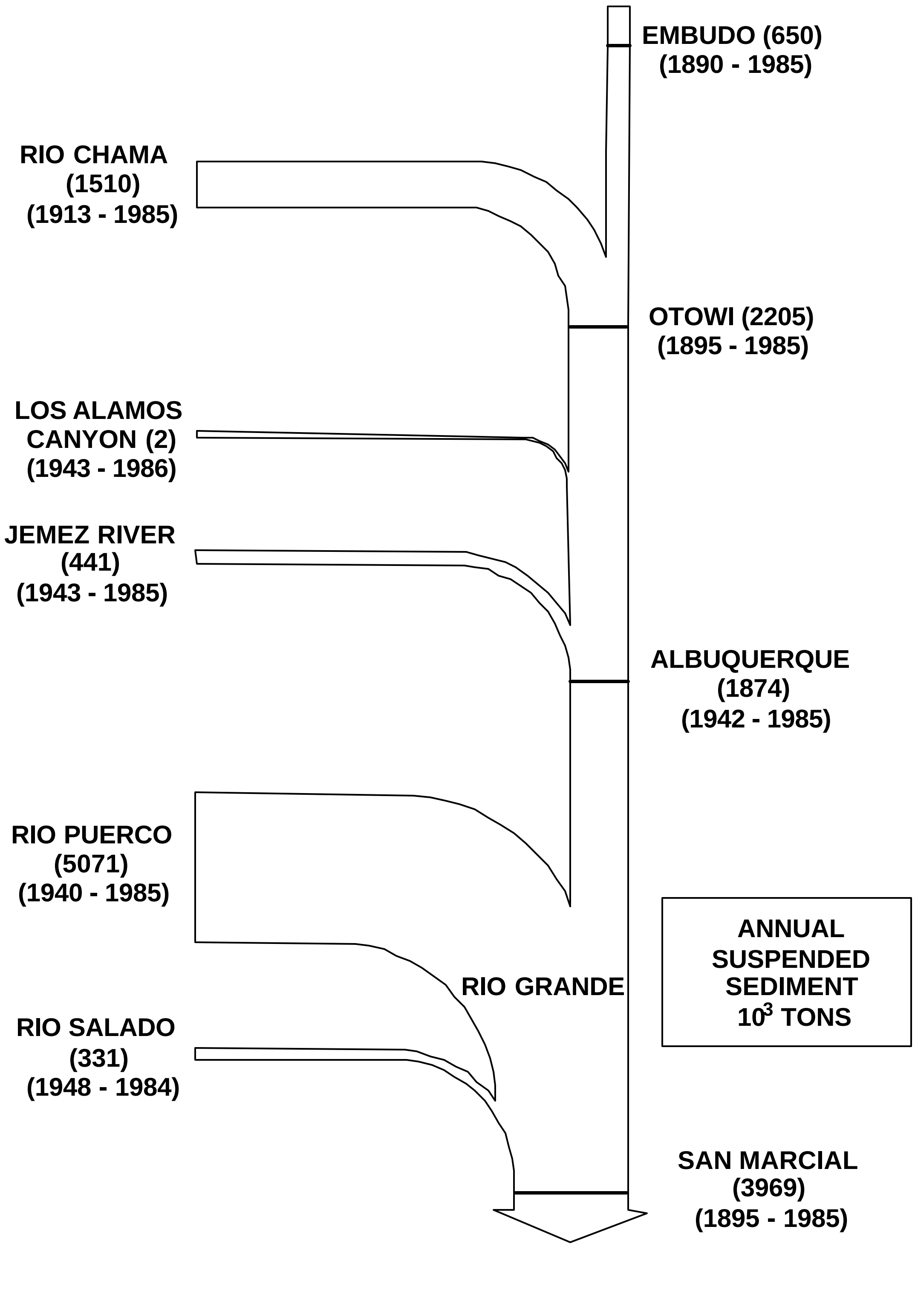


Figure 1.4. Flow diagram for the annual budget for suspended sediment in the Northern Rio Grande (Graf, 1994). The indicated values are averages for the period between 1948 and 1984.

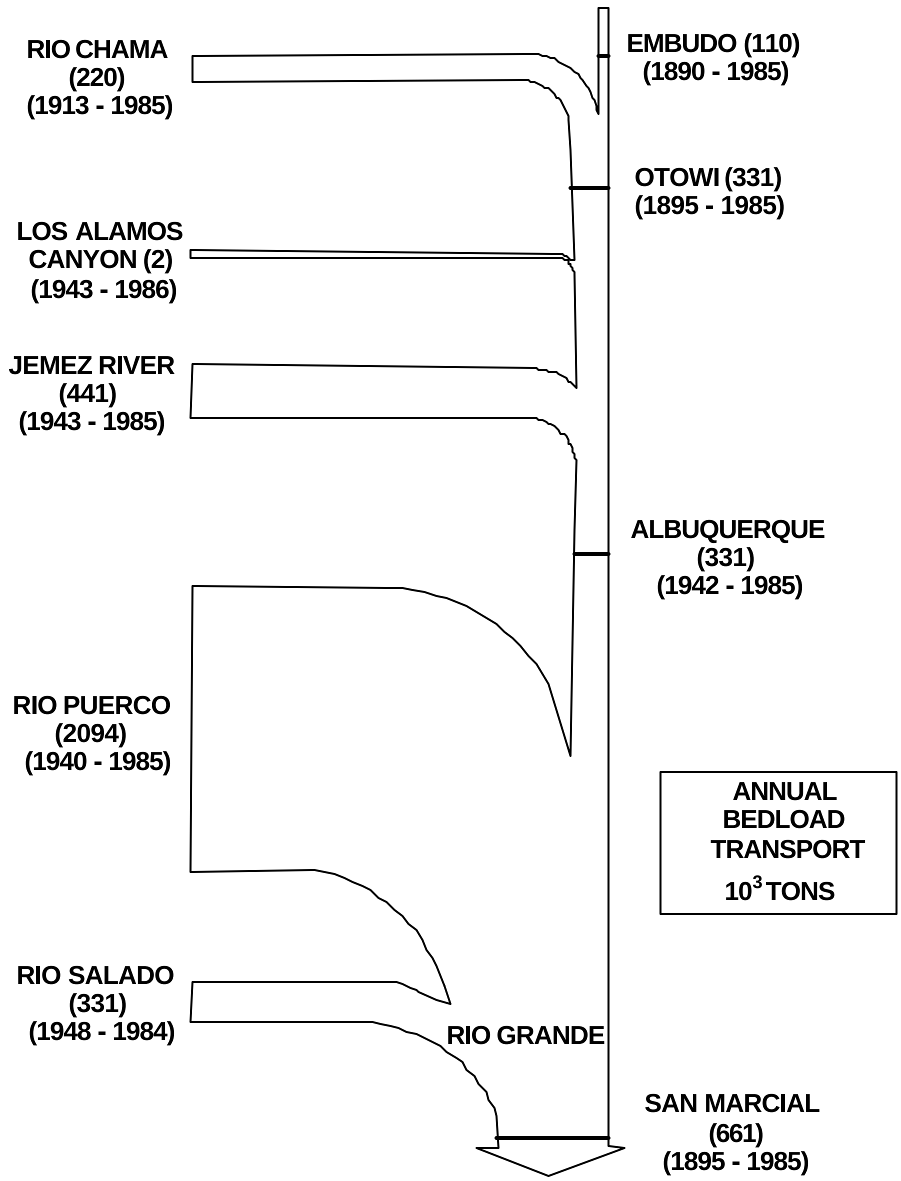


Figure 1.5. Flow diagram for the annual budget for bed-load sediment in the Northern Rio Grande (Graf, 1994). The indicated values are averages for the period between 1948 and 1984.

1.3. Authorization

This investigation of the geomorphology and sedimentology of the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir was conducted by Mussetter Engineering, Inc. (MEI) under subcontract to S.S. Papadopulos and Associates (SSP&A) for the New Mexico Interstate Stream Commission (NMISC) under Work Order SSPA RGWO L4. Dr. Nabil Shafike was the project manager for the NMISC. The MEI project was managed by Dr. R.A. Mussetter, P.E., and the work was conducted by, and under the supervision of, Drs. S.A. Schumm, P.G. and M.D. Harvey, P.G. We thank the numerous individuals who were very helpful in obtaining information and data, especially Ms. Dagmar Llewellyn (SSP&A), Mr. Robert Padilla (USBR), Mr. Daryl Eidson (COE), Mr. Drew Baird (USBR), Dr. Mike Marcus (SWCA) and Dr. Pierre Julian (Colorado State University).

1.4. Sources of Information

In order to achieve the project objectives, a geomorphic and sedimentologic evaluation of the Middle Rio Grande was completed, which relied primarily on available data and one reconnaissance of the river between Cochiti Dam and Elephant Butte Reservoir. The reconnaissance included an overflight of the river and reservoir between Cochiti and Truth or Consequences on March 15, 2001. Photographs taken during this overflight and field reconnaissance are included in **Appendix A** The report is based upon survey data provided by the U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, NMISC, 7.5-minute topographic maps, aerial photographs taken in 1935, 1962, 1972, 1992 and 1997, and maps from 1917 through 1918. A literature search was conducted and the identified literature was reviewed, including published papers and books as well as unpublished reports, theses, and dissertations. Especially useful were the book by Graf (1994), and theses by Bauer (2000), Leon (1998), and Richard (2001), the unpublished report by Lagasse (1980), and the Middle Rio Grande Ecosystem report authored by Crawford et al (1993). A bibliography of reviewed literature is provided in **Appendix B**.

Large amounts of data have been compiled by various authors. For example, for numerous cross sections, Bauer (2000) discussed changes of channel dimensions for the pre-Cochiti Dam period (1970-1973) and the post-dam period (1974-1998) for the reach of river from Bernalillo to San Acacia. Leon (1998) detailed the channel changes from Cochiti to Bernalillo, and Richard (2001) studied channel planform change and lateral channel change from Cochiti to Bernalillo. Lagasse (1980) investigated the impact of Cochiti Dam on the channel downstream. All available USBR survey and sediment data on the Rio Grande have been compiled by Professor Pierre Julien and his students at Colorado State University under contract to the USBR, and this information was made available to MEI.

Additionally for this investigation, hydrologic and sediment data were obtained for the published periods of record from the USGS gages at Otowi, Cochiti, San Felipe, Bernalillo, Albuquerque, Bernardo, San Acacia, and San Marcial. MEI collected bed-material sediment samples at 22 locations as part of this project. Vinyard & Associates, Inc. in Albuquerque, conducted sieve analyses of these samples.

To facilitate data compilation and comparison from various sources and time periods, MEI developed a station line for the project reach. The station line was digitized from the USGS georeferenced digital orthoquads (1996 through 1998; provided by NMISC) for the reach from Elephant Butte Reservoir to San Acacia, and from the photo-revised USGS 7.5-minute quadrangles for the reach from San Acacia to Cochiti Dam. The digitized station line was smoothed using the cubic spline routines in AutoCAD (v.14). The origin of the station line (Station 0+00) is the downstream end of the levee that borders the east bank of the Low Flow Conveyance Channel (LFCC), located about 9 miles below the BNSF railroad bridge at San Marcial. Negative values on the station line represent locations downstream of the origin, primarily associated with the pilot channel constructed within the upper end of the reservoir. USBR range lines (cross sections) and river miles (RM: RM 0 is Caballo Dam) have been related to the MEI station line and a listing of range lines by station and river mile is provided in **Appendix C**. For reference purposes, **Table 1.1** provides the locations of identified features within the project reach in terms of MEI stationing (feet), river miles (upstream of Caballo Dam) and river miles downstream of Cochiti Dam.

Although much of the cited work was concentrated between Cochiti and Bernalillo, the early maps and aerial photographs provide a basis for study of the river between Cochiti and Elephant Butte Reservoir. The river between these end points can be described as braided, but the river was, and is still, highly variable as a result of both natural controls and human activities.

Table 1.1. Locations of identified features within the project reach shown in terms of the MEI stationing (feet) and River Miles (upstream of Caballo Dam) obtained from the 1997 USBR River Atlas.

Location	MEI Station (ft)	RM Upstream of Caballo Dam	RM Downstream of Cochiti Dam
Cochiti Dam	907200	232.3	---
San Felipe (gage)	820000	216.1	16.2
Angostura Diversion	788800	209.7	22.6
Bernalillo (NW44) (gage)	759650	203.8	28.5
I-40 Bridges	659700	185.0	47.3
Central Avenue Bridge (gage)	652100	183.4	48.9
I-25 Bridges	595050	172.6	59.7
Isleta Diversion	578200	169.2	63.1
Los Lunas (NM Hwy 49)	536250	161.4	70.9
Belen (NM Hwy 6)	577000	149.5	82.8
Bernardo (US 60 Bridge/gage)	380300	130.6	101.7
Canada Ancha	325800	120.6	112.0
San Acacia Diversion (gage)	301500	116.2	116.1
Escondida/Pueblito Bridge	244000	104.8	127.5
San Antonio (US 380)	162700	87.1	145.2
San Marcial Railroad Bridge (gage) (BNSF)	47600	68.6	163.7

1.5. Summary of Literature Review

A review of the literature pertaining to geology, geomorphology, sediment transport, engineering practices, and riparian vegetation of the Middle Rio Grande resulted in the identification of seven general conclusions reached by numerous investigations. These conclusions are listed below with appropriate references.

1. The channel of the Middle Rio Grande has narrowed. The narrowing began prior to the closure of Cochiti Dam, and it may be the result of reduced sediment delivery from tributaries as well as water diversions and engineering structures (Carter, 1955; Dewey et al., 1979; Graf, 1994; Lagasse, 1994).
2. The channel of the Middle Rio Grande has deepened. Degradation is probably the result of reduced sediment loads and channel narrowing (Baird, 2001; Lagasse, 1994).
3. The channel of the Rio Grande downstream of Cochiti Dam has armored as a result of reduced sediment loads (Lagasse, 1994).
4. The Middle Rio Grande has changed from a braided channel to a single channel as a result of reduced bed load (Culbertson and Dawdy, 1964; Graf, 1994; Lagasse, 1994).
5. Riparian vegetation along the Middle Rio Grande has changed and it reflects former channel locations (Ellis, 1996; Everitt, 1998; Graf, 1994; Taylor, 1999).
6. Sediment characteristics vary from reach to reach of the Middle Rio Grande as a result of tributary influences (Culbertson et al., 1972; Graf, 1994; Happ, 1948; Nordin and Beverage, 1963; Rittenhouse, 1944).
7. The Middle Rio Grande is significantly affected by geologic controls. Between Belen and Socorro, active uplift has caused changes in gradient. Earthquakes are concentrated in this reach and at Albuquerque (Reilinger et al., 1979, 1980; Sanford et al., 1979, 1991; Schumm et al., 2000).

2. REACH IDENTIFICATION AND RIVER VARIABILITY

In order to study a river as variable as the Rio Grande, reaches of generally similar morphology should be identified. The different response of these reaches to natural and human impacts provides a guide for understanding river behavior. For example, the effects of dams on rivers have been investigated by civil engineers and geomorphologists in order to determine how changed hydrology and reduced sediment loads impact the river downstream (Williams and Wolman, 1984; Collier et al., 1996). Williams and Wolman (1984) concluded that the downstream effects are highly variable with degradation below a dam being of little or great significance, and the downstream effect being short or long. For example, tributary contributions downstream of a dam can inhibit degradation and, in fact, the Rio Grande below Elephant Butte Dam has aggraded.

Obviously, armoring, bedrock, and human activities will significantly alter the downstream impacts of a dam. For example, Williams and Wolman (1984), in selecting dam sites for downstream study, rejected sites where there was significant dredging and channelization. This may also be the reason that Collier et al. (1996) did not select the Rio Grande downstream of Cochiti Dam for study.

2.1. Reach Identification

The Middle Rio Grande from Cochiti Dam to Elephant Butte Reservoir has been subdivided into different reaches by a number of authors. For example, Graf (1994) divided the reach into seven representative subreaches that were based on the existing characteristics of the river at the time of his study. Crawford et al. (1993) utilized a four-reach subdivision also based on existing conditions along the river (Cochiti Reach, Albuquerque Reach, Belen Reach, Socorro Reach). The USBR has identified a number of different reaches for different purposes, but in general (USBR, 1977) uses a four-reach subdivision (Cochiti to Angostura, Angostura to Isleta, Isleta to San Acacia, San Acacia to San Marcial). Based on water supply and drainage facilities the Middle Rio Grande Conservancy District (MRGCD) has subdivided the reach into four subreaches that are the same as those used by Crawford et al. (1993).

For the purposes of this investigation, nine subreaches of the river have been recognized and identified. The reach subdivision was done on the basis of geomorphic and geologic controls that historically governed the sediment storage potential, and hence the behavior of the river within the Middle Rio Grande. The identified subreaches are valley-wide sediment storage zones that are located upstream of identified valley width constrictions. The sediment storage zones represent the historical channel of the Rio Grande and its floodplain prior to any man-made interventions. The widths of the sediment storage zones (measured at 1-mile intervals through the reach) and the downstream controls (measured at the point of constriction of the valley) were derived from the 7.5-minute USGS topographic maps of the valley.

Table 2.1 identifies the individual reach boundaries and their locations with respect to the MEI station line and the USBR river miles. Four structural basins (grabens) make up the valley of the Middle Rio Grande (Lozinsky and Tedford, 1991; Smith et al., 2001) and their boundaries coincide with some of the subreach boundaries identified in Table 2.1. Reach 1 boundary coincides with the southern margin of the Santo Domingo Basin, Reach 3 boundary coincides with the southern margin of the Albuquerque Basin, Reach 5 boundary coincides with the southern margin of the Belen Basin, and Reach 8 boundary coincides with the southern margin of the Socorro Basin.

Table 2.1. Subreach boundary identification for the Middle Rio Grande based on the presence of geologic and geomorphic controls.

Graf (1994) Reach	MEI Reach	Boundaries	Station (ft)	River Miles	Reach Length (ft/miles)
1	1	Cochiti Dam to San Felipe	907200 - 820000	232.3 - 216.1	85,536/16.2
	2	San Felipe to Angostura Diversion	820000 - 788800	216.1 -209.7	33,792/6.4
2, 3	3	Angostura Diversion to Isleta Diversion	788800 - 578200	209.7 - 169.2	213,840/40.5
4	4a	Isleta Diversion to Belen	578200 - 477000	169.2 - 149.5	104,016/19.7
5	4b	Belen to Canada Ancha	477000 - 325800	149.5 - 120.6	152,592/28.9
	5	Canada Ancha to San Acacia Diversion	325800 - 301500	120.6 -116.2	23,232/4.4
6	6	San Acacia Diversion to Escondida	301500 - 244000	116.2 - 104.8	76,032/11.4
	7	Escondida to San Antonio	244000 - 162700	104.8 - 87.1	93,456/17.7
7	8	San Antonio to San Marcial	162700 - 47600	87.1 - 68.6	97,680/18.5

Table 2.2 presents the valley width data for each of the sediment storage zones and downstream valley constrictions. The constrictions are generally created by either less erodible bedrock outcrop on both sides of the valley (Reaches 3, 4b and 5), a combination of bedrock outcrop on one side of the valley and a large tributary alluvial fan on the other side of the valley (Reaches 1, 2, 6, 8), or by two opposed tributary alluvial fans (Reach 7 and possibly Reach 2). With the exception of Reach 4, the ratios of the average valley width to the width of the downstream constriction range from about 3 to 5. However, the ratio for Reach 4 is about 12, and this probably reflects the influence of the active Belen-Socorro Uplift (Ouchi, 1985) (see Chapter 3 for a more detailed discussion of the effects of the uplift).

Graf (1994) identified seven representative reaches of the present Rio Grande channel between Cochiti Dam and Elephant Butte Reservoir. Table 2.1 provides a correlation between the MEI and Graf (1994) reaches. The details of Graf's (1994) reaches are included because they provide a good summary of the man-made modifications to the Middle Rio Grande.

1. Peña Blanca (35°35'N, 106°20'W). This 3-mile section represents conditions common along the 24-mile reach of the Rio Grande between Cochiti Dam and the Jemez River confluence. It is representative of unstable reaches in a broad alluvial valley without extensive urban development.

2. Coronado (35°20'N, 106°32'W). This 3-mile section is typical of the 15-mile reach between the Jemez River and Albuquerque, which represents a partly confined channel with a levee on one side and major impacts of the Jemez River and smaller tributaries.

3. Los Griegos (35°48'N, 106°36'W). This 3-mile section is representative of the 15-mile reach through Albuquerque. The channel is confined by levees in an urban area.

Table 2.2. Summary of average valley width data for identified subreaches of the Middle Rio Grande.			
Reach	Average Valley Width (ft)	Width of Downstream Valley Constriction (ft)	Description of Downstream Geologic and Geomorphic Control
1	7,085	1,500	Bedrock outcrop on the west and Arroyo Tonque fan on the east
2	6,975	2,000	Bedrock outcrop on the west and Las Huertas Creek fan on the east (could also be the fan of the Jemez River on the west)
3	11,790	3,000	Bedrock outcrop on the east and west
4a	18,030	-	Upstream limit of Belen-Socorro Uplift
4b	10,640	1,200	Bedrock outcrop on the east and west
5	4,125	1,000	Bedrock outcrop on the east and west
6	9,030	1,800	Bedrock outcrop on the west and the fan of Arroyo de la Parida on the east; downstream limit of Belen-Socorro Uplift
7	8,660	3,000	Fan of Walnut Creek on the west and the fan of San Pedro Arroyo on the east
8	11,100	3,200	Bedrock outcrop on the east and alluvial terraces on the west

4. Los Lunas (34°48'N, 106°43'W). This 3-mile reach is representative of about 42-mile reach from Albuquerque to Bernardo, a transition from urban to rural land use. Levees are farther apart than in Reach 3.

5. San Geronimo (34°22'N, 106°50'W). This 3-mile reach is representative of the 15-mile segment between the Bernardo Bridge and the San Acacia Diversion. This reach is strongly influenced by the Rio Puerco and Rio Salado.

6. Chamizal (34°14'N, 106°55'W). This 3-mile reach represents 24 miles of the Rio Grande between San Acacia Diversion and San Antonio. This reach contains a wide channel with a pilot channel and the San Lorenzo sediment detention basin and the northern part of the Bosque del Apache National Wildlife Refuge.

7. San Marcial (33°45'N, 106°53'W). The 4.8-mile reach represents conditions between San Antonio and the San Marcial Bridge. This reach is in the Bosque del Apache National Wildlife Refuge and is in the backwater of Elephant Butte Reservoir.

2.2. River Variability

Information on geologic and geomorphic controls and the 1917/1918 maps were used to identify the more or less natural characteristics of the river in nine subreaches of the project reach (Table 1.2 and Figure 1). However, the characteristics of the present day river, including a significant amount of the variability within individual reaches, is dependent on man-made interventions. Comparisons of the river characteristics in 1917/1918 and conditions observed on the 1962, 1972, and 1992 aerial photographs are summarized by reach in the following paragraphs.

- Reach 1 (Cochiti to San Felipe) in 1917-1918 contained an anastomosing multi-channeled river (**Figure 2.1**). Large vegetated islands separated channels of approximately equal width. Between 1962 and 1992, some channels were abandoned and by 1992, there was essentially a single channel between Cochiti and San Felipe. For example, between Sta. 908594 (RM 230.2) and Sta. 896590 (RM 232.5), there were three active channels in 1962, but in 1992, the side channels were vegetated. Also, dredging has cut off bends and straightened the channel.
- The Reach 2 channel (San Felipe to Angostura) in 1917-1918 was anastomosing (**Figure 2.2**), but one channel was predominant. In 1962 through 1992, a single channel was relatively straight and braided through this reach.
- The Reach 3 channel (Angostura to Isleta) was wide and braided in 1917-1918 (**Figure 2.3**). Large sand bars flanked the channel and divided the flow. Channel width was highly variable. In general, in 1962 through 1992, the channel was wide and braided, but width was determined by dike fields and dredging.
- Reach 4a (Isleta to Belen), in 1917-1918, contained a single braided channel of varying width (**Figure 2.4**). Subsequently, the channel has been narrowed by dike fields and dredging.
- Reach 4b (Belen to Canada Ancha) contained a variable-width braided channel in 1917-1918 (**Figure 2.5**), which widened greatly, as a result of sediment contribution from Rio Puerco. Subsequently, dredging has narrowed the channel.
- Reach 5 (Canada Ancha to San Acacia) lies on the crest of the Belen-Socorro Uplift and the narrow channel is confined by bedrock (**Figure 2.6**). However, downstream of the junction of Rio Salado, the valley widens and sediment is stored upstream of the San Acacia constriction.
- Reach 6 (San Acacia to Escondida), in 1917/1918, contained a very wide and braided channel (**Figure 2.7**). The sediment contributions from the Rio Puerco and Rio Salado, as well as the east-side tributary arroyos were responsible for the very wide braided condition of the channel. There was considerable dredging of the channel in this reach before 1962 and up to 1992.
- Reach 7 (Escondida to San Antonio) contained a wide braided channel (**Figure 2.8**) with low sinuosity in 1917-1918 between Socorro and San Antonio. The width of the channel was highly variable between 1962 and 1992.
- Reach 8 (San Antonio to San Marcial), in 1917-1918, contained a slightly sinuous channel, but it was wandering rather than meandering (**Figure 2.9**). Subsequently, the channel was dredged and straightened. Downstream of the Bosque del Apache NWR, the channel is now completely man-made.

The 1917/1918 channel longitudinal profile (**Figure 2.10**) that was digitized from the 1917/1918 maps shows a generally decreasing gradient in the downstream direction. In the upper two reaches (1,2) where the bed of the channel was gravel (Culbertson and Dawdy, 1964; Crawford et al., 1993) the bed slope is steep at about 0.1 percent (about 5.3 feet/mile). In the finer-grained, sand-bed reaches the slope is flatter and ranges from about 0.0007 to 0.0009 (3.7 to 4.8 feet/mile). The profile does clearly demonstrate the effects of the Belen-Socorro uplift. Upstream of the uplift, the slope is somewhat flattened to about 0.00071 in Reach 4b, it increases to 0.00085 on the downstream limb of the uplift (Reaches 5 and 6), and flattens again to about 0.00075 downstream of the influence of the uplift (Reaches 7 and 8).

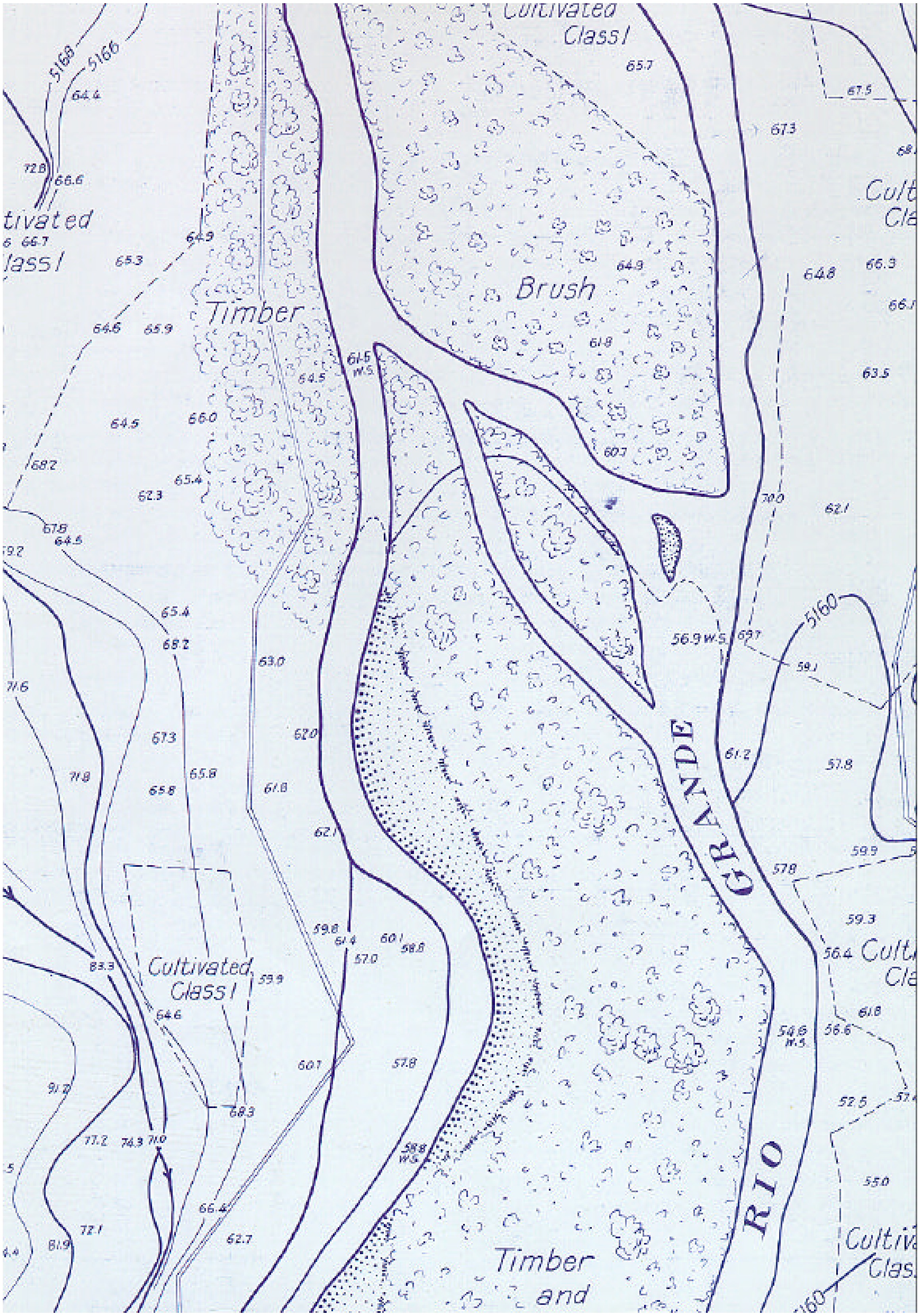


Figure 2.1. A portion of the 1917/1918 map of the Rio Grande showing the anastomosed channel planform in Reach 1. The channels appear to be the same size.

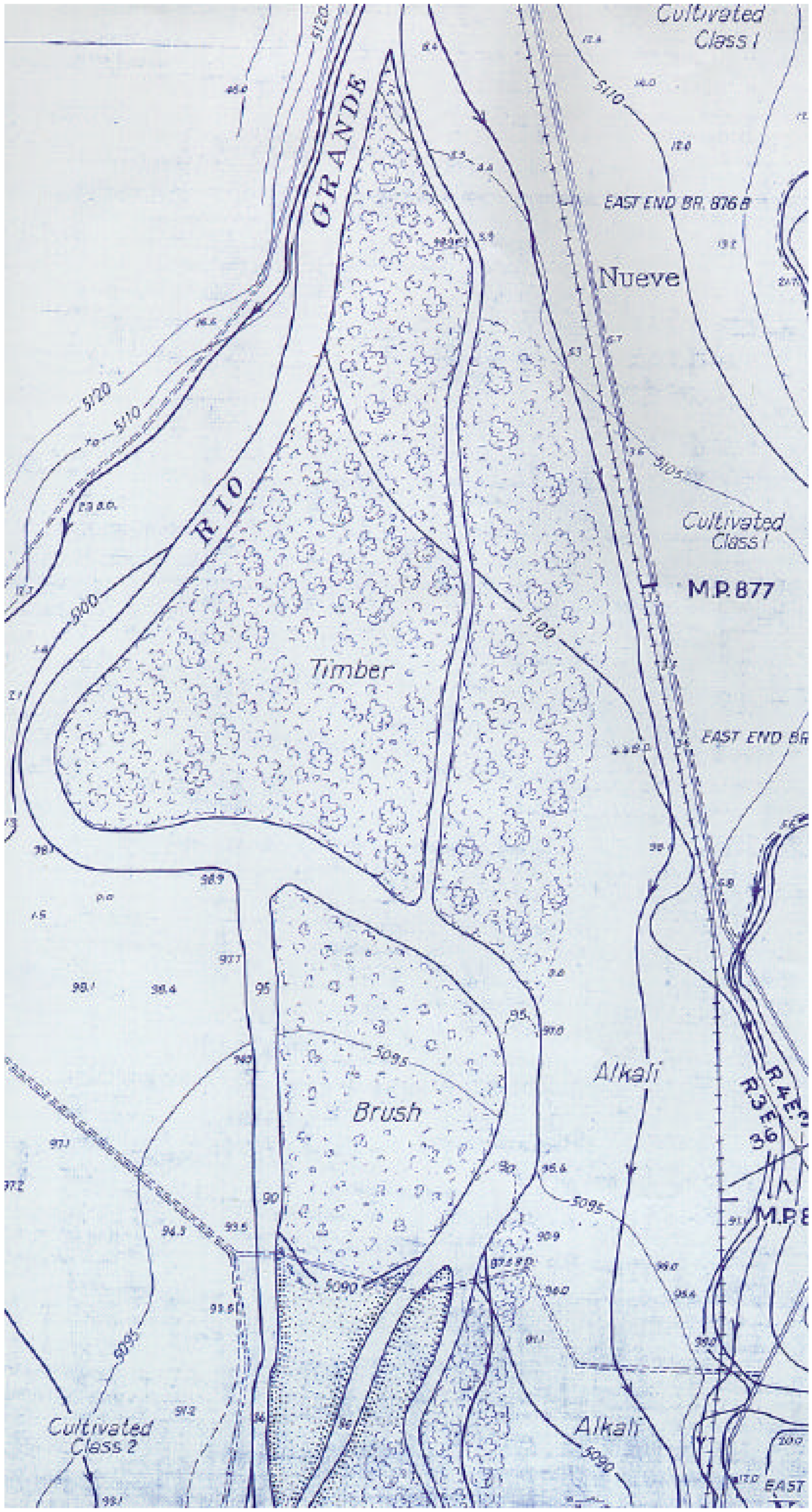


Figure 2.2. A portion of the 1917/1918 map of the Rio Grande showing the anastomosed channel planform in Reach 2. In contrast to Reach 1, one of the channels appears to be dominant.

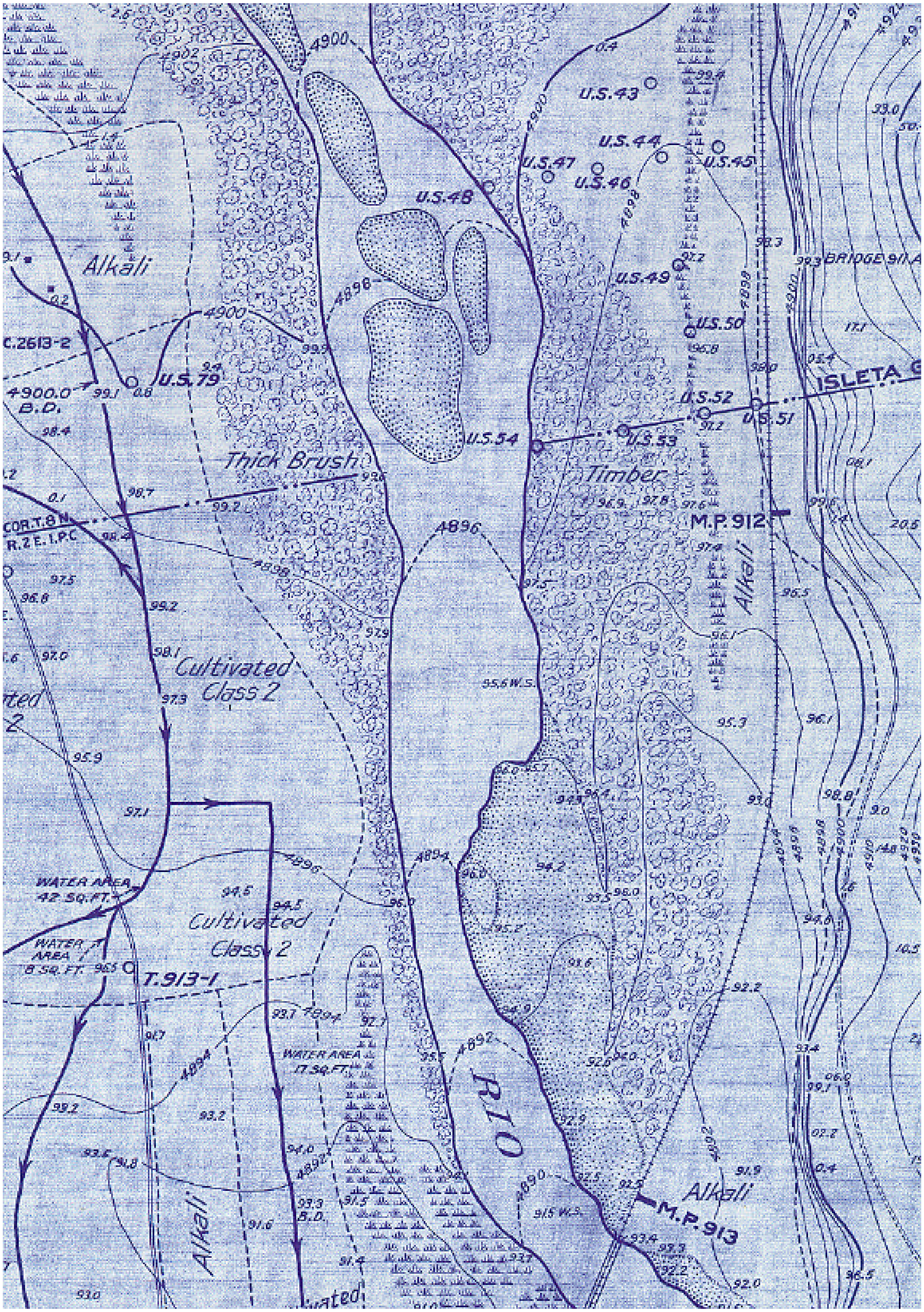


Figure 2.3. A portion of the 1917/1918 map of the Rio Grande showing the braided planform with highly variable channel width and numerous mid-channel bars in Reach 3.

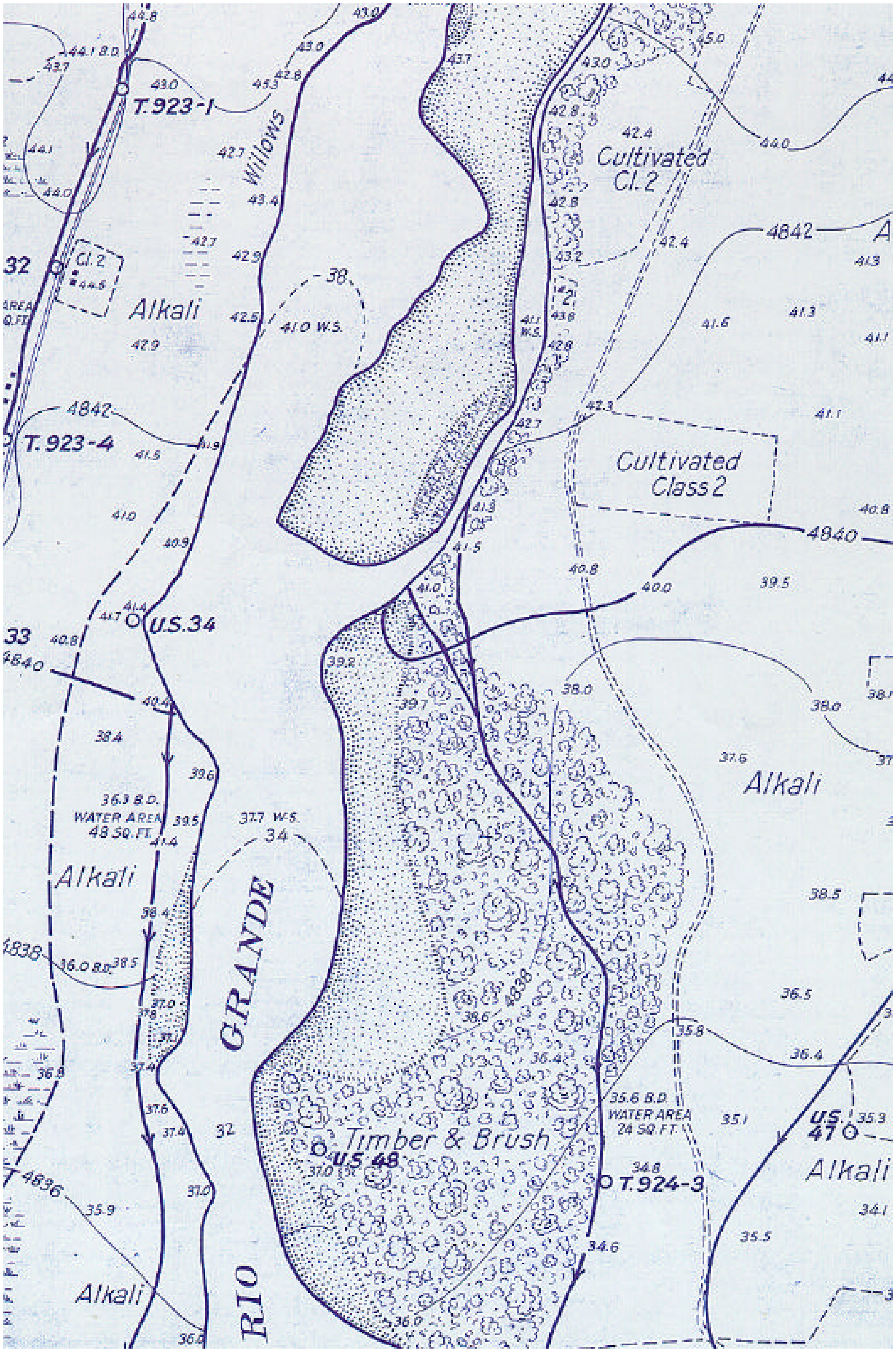


Figure 2.4. A portion of the 1917/1918 map of the Rio Grande showing the braided planform with highly variable channel width in Reach 4a.

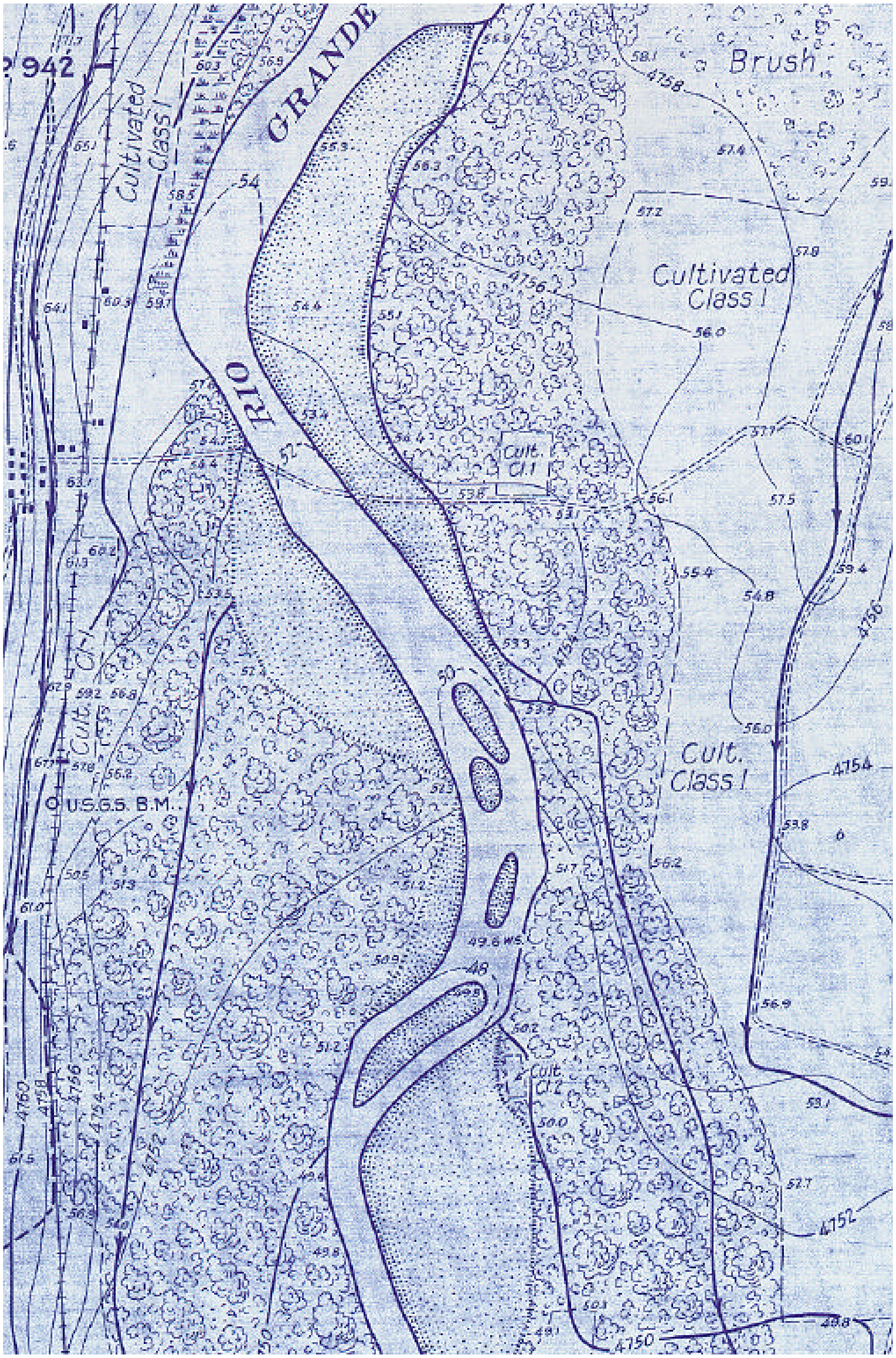


Figure 2.5. A portion of the 1917/1918 map of the Rio Grande showing the braided planform with highly variable channel width and numerous mid-channel and lateral bars in Reach 4b.

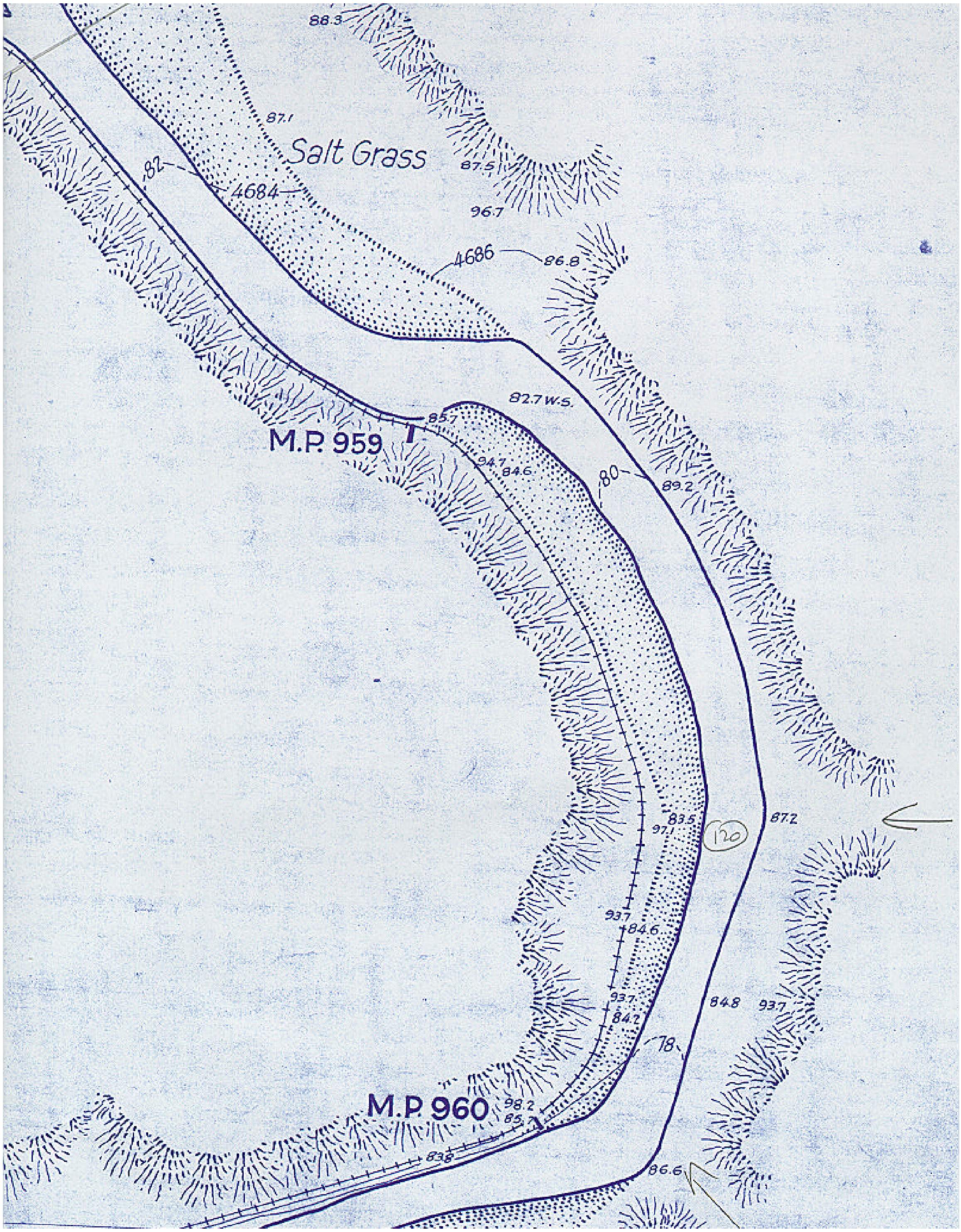


Figure 2.6. A portion of the 1917/1918 map of the Rio Grande showing the narrow, bedrock-controlled channel in the upstream part of Reach 5. Alternate bars characterized this part of the river.

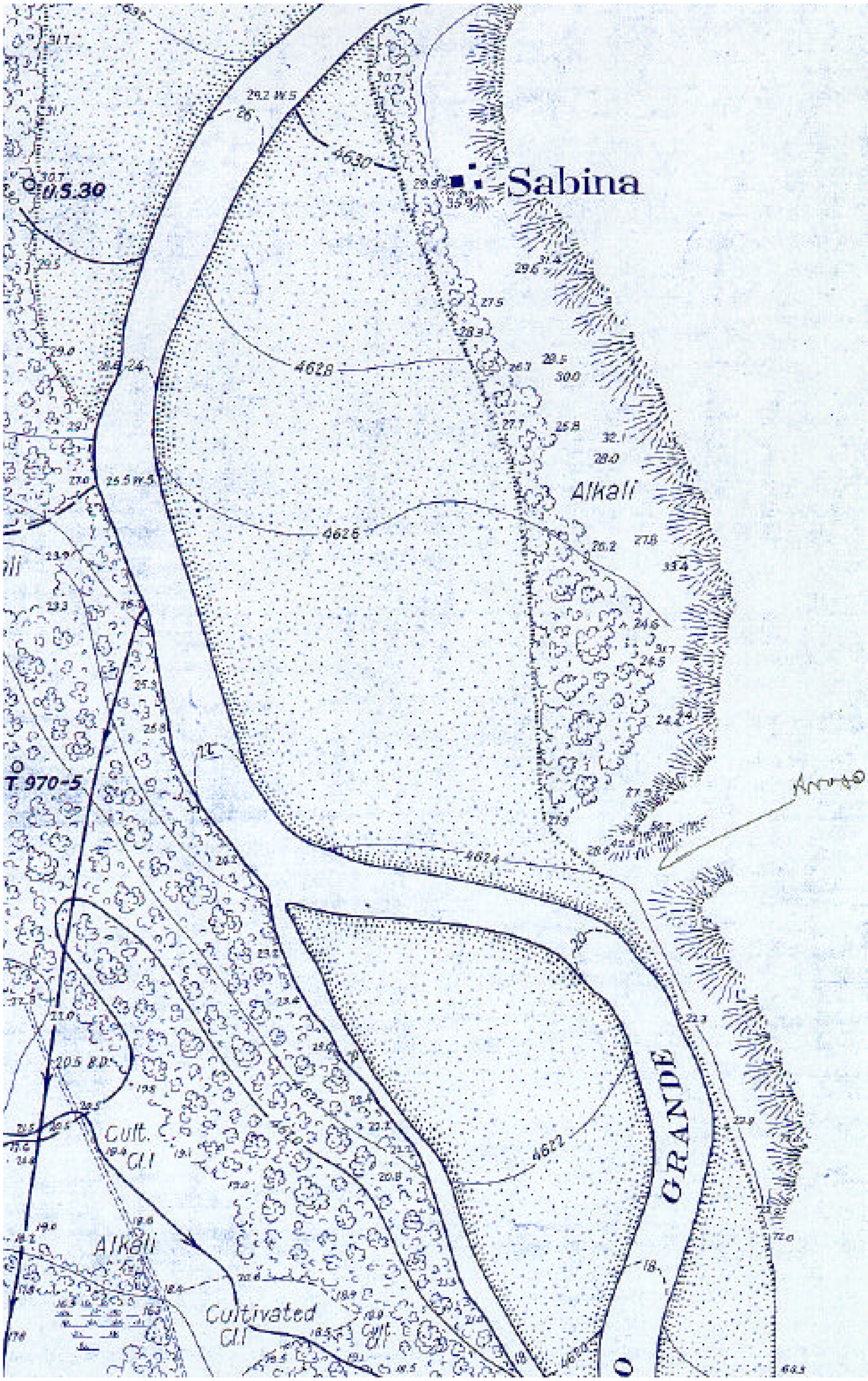


Figure 2.7. A portion of the 1917/1918 map of the Rio Grande showing the braided planform and large mid-channel bars in Reach 6 where numerous east-side arroyos episodically delivered large volumes of sediment to the channel.

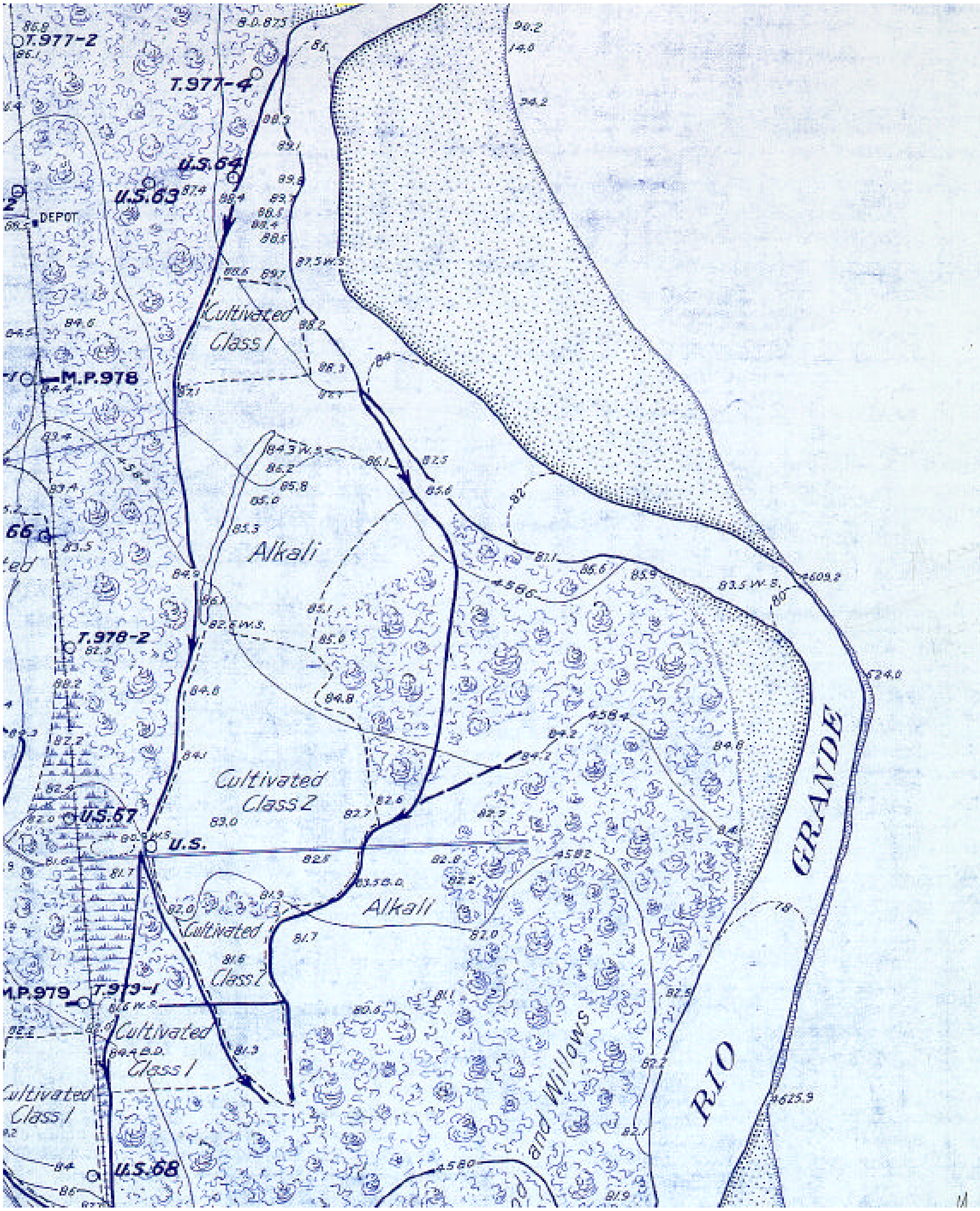


Figure 2.8. A portion of the 1917/1918 map of the Rio Grande showing a low sinuosity planform in Reach 7. The low sinuosity planform is probably related to the higher proportion of fine-grained sediments introduced by the Rio Puerco degradation.

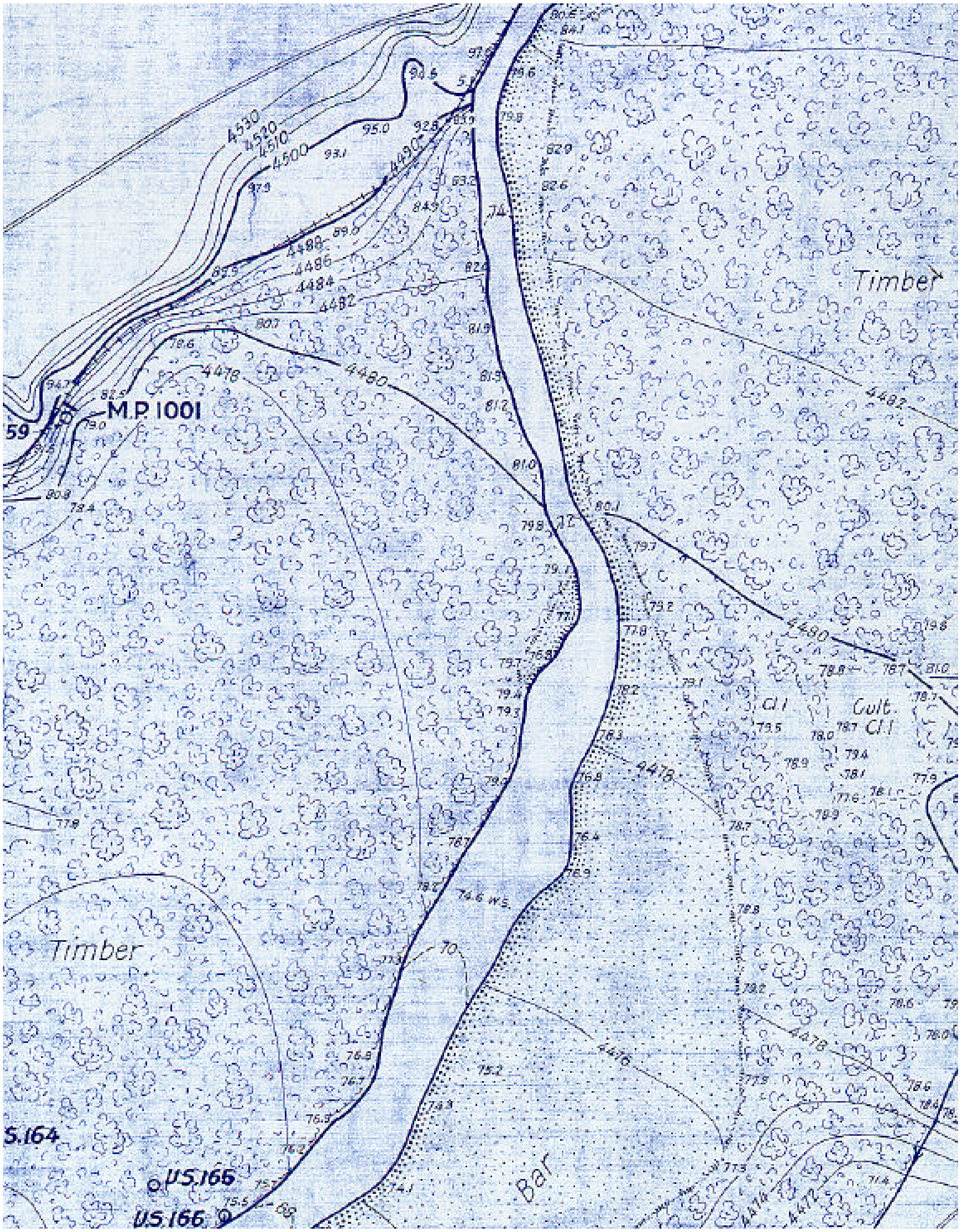


Figure 2.9. A portion of the 1917/1918 maps of the Rio Grande showing a slightly sinuous, but highly variable width channel in Reach 8. The sinuosity and narrow channel is probably related to the high fine-sediment load and somewhat flatter gradient.

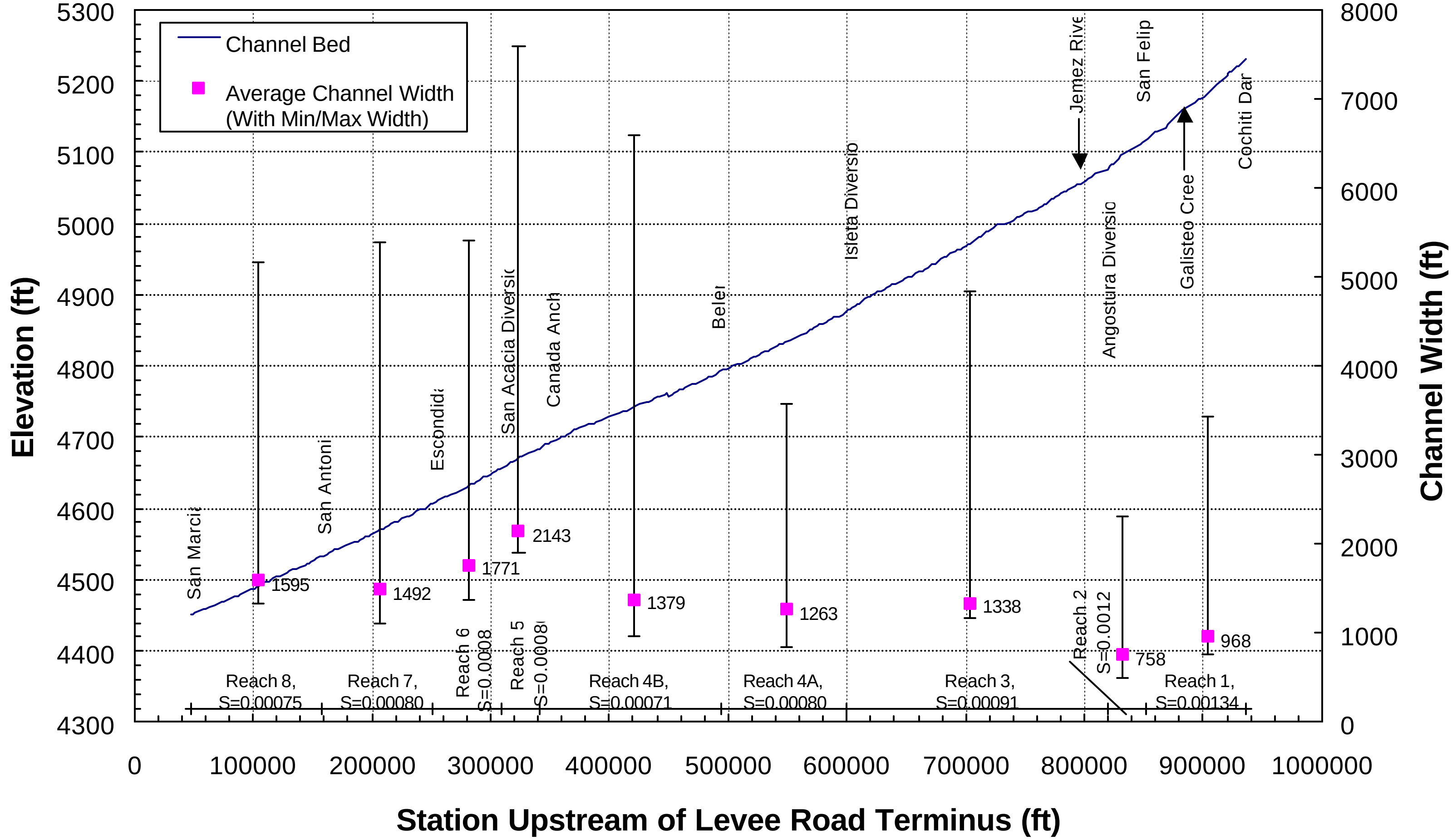


Figure 2.10. Longitudinal profile of the Rio Grande developed from the 1917 -1918 survey of the river. The bed slopes as well as the average active channel width and maximum and minimum widths for each of the identified reaches are also shown.

The average channel width data derived from measurements of active channel width between the mapped vegetation boundaries at each marked contour interval across the channel in the 1917/1918 survey maps show a general increase in the average channel width in the downstream direction (Figure 2.10). Also shown are the maximum and minimum width values for each of the subreaches. Average channel width increases progressively from 968 feet in Reach 1 to about 2,143 feet in Reach 5, and it then declines to 1,595 feet in Reach 8. The large increase in width between Reach 4b (1,379 feet) and Reach 5 (2,143 feet) probably reflects the increase in sediment supply from the entrenched Rio Puerco, and the Rio Salado that is deposited upstream of the San Acacia valley constriction. Not only does the average channel width increase in the downstream direction, but the variability of channel width increases as well. The high variability shown in Reach 4b is probably due to the effects of the Belen-Socorro uplift (i.e., the flattened slope), but in Reaches 5, 6, 7 and 8 the variability most probably reflects the very high sediment input from the major tributaries (Rio Puerco and Rio Salado) as well as the very high number of east-side tributary arroyos (Figure 1).

The 1917/1918 slope data were combined with estimations of the mean annual discharge, based on gage data for the pre- and post-Cochiti period, for the individual reaches, to evaluate channel planform thresholds (**Figure 2.11**). The Lane (1957) thresholds for meandering and braided channels are shown on the figure, as are the plotting positions for the individual reaches for the two periods. All of the reaches plot in the transitional zone between braided and meandering channels, with the coarser bed-material reaches plotting closer to the braided threshold as expected (Ferguson, 1984; Carson, 1984). The anastomosing nature of the two upstream reaches on the 1917-1918 maps could be due to reduced flows as a result of early water resource development projects in the upper basin. The National Resource Commission (1938) reported that the natural flows in the Rio Grande in the upper basin had been reduced by 40 to 60 percent by 1890, and Jones and Harper (1998) reported that mean annual discharge decreased by 60 to 70 percent from 1875 to 1925 at the Del Norte gage. They concluded that changes in channel planform characteristics were related to the reduced discharge, and that the channel became considerably more stable in the periods following 1875.

For the remainder of the reaches that fall in the transitional category on Figure 2.11, it is not surprising that the reaches display characteristics of both meandering and braided channels. However, the reaches should probably be referred to as wandering rather than meandering (Desloges and Church, 1989). Although they show some characteristics of meandering channels, channel change tends not to be systematic through time, but is more likely to be avulsive (Mussetter and Harvey, 2001). In wandering channels, planform changes are irregular and they are controlled by episodic flood flows. During periods between high-magnitude flood events, a measure of sinuosity develops as a result of lateral migration of the channel. However, when relatively infrequent large floods occur, bends of almost any radius of curvature cut off and the channel sinuosity is significantly reduced and the channel planform becomes braided. The development of large bends that provided temporary sediment storage sites, and then cut off during flood flows, appears to be characteristic of the Middle Rio Grande (**Figure 2.12**) (Happ, 1948).

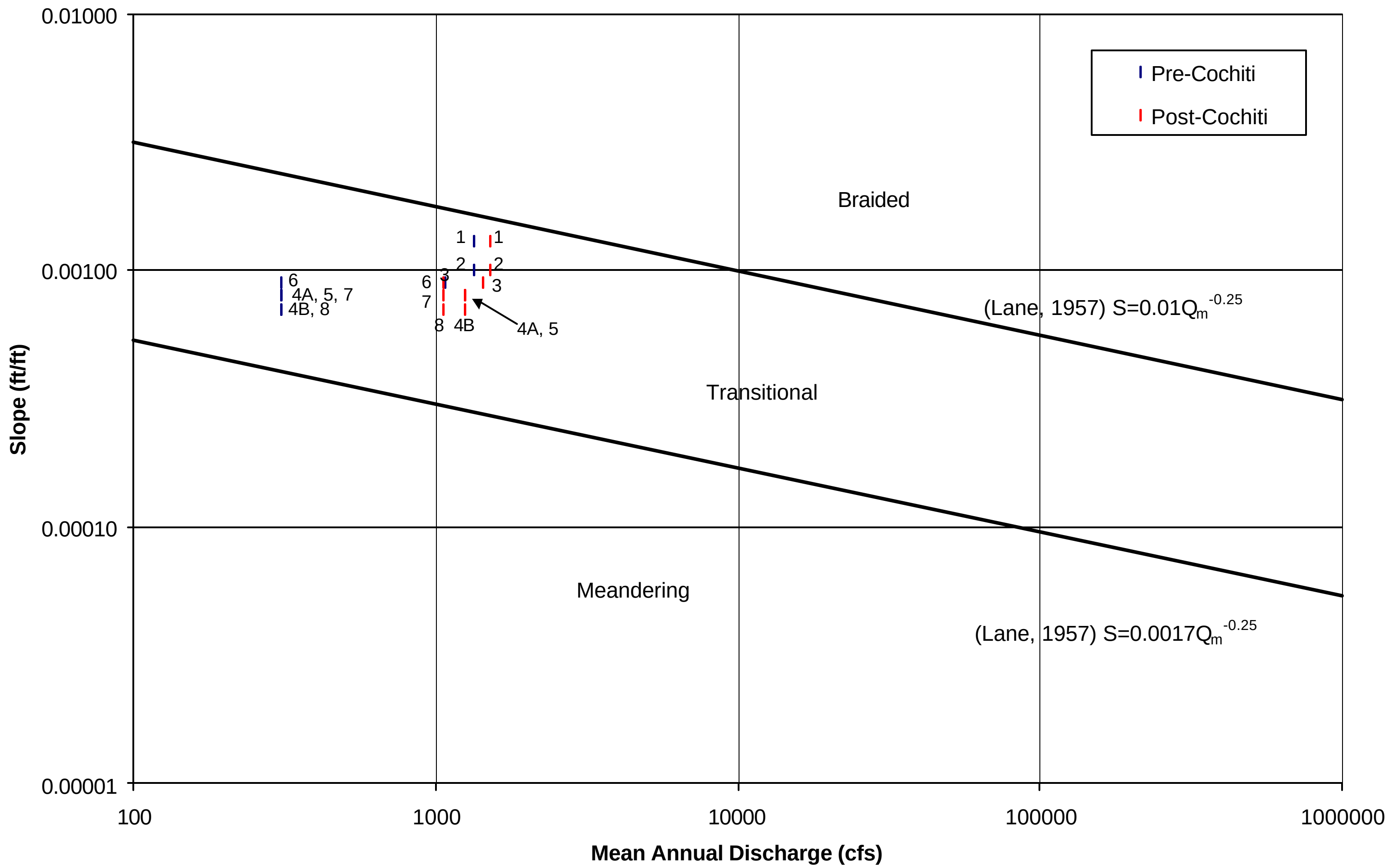


Figure 2.11. Plot of pre- and post-Cochiti mean discharge against channel slope showing the threshold lines for braided and meandering channels developed by Lane (1957). The individual reaches all plots in the transitional category between meandering and braided.

Figure 2.12. 1935 aerial photograph (#5933A) of a reach of the Rio Grande in the vicinity of the Bosque del Apache National Wildlife Refuge (RM 80 – RM 83, Reach 8) showing sections of a moderately sinuous meandering channel (Sinuosity 1.4) that was probably abandoned in the floods of 1929 and early 1933.

3. CONTROLS

The variability of the Middle Rio Grande channel among and within reaches indicates that there are several significant controls on river morphology and behavior. Although the Rio Grande is for the most part an alluvial river with its channel composed of sediments currently transported by the river, geology plays an important role in river character and response. Hydrologic changes in the basin have been substantial, and have affected river character and response. Sediment supply, transport, and deposition have been modified through time and have affected the form and characteristics of the river as well as the gradation of the bed material. Finally, much of the variability is associated with man-made interventions for irrigation and drainage, flood control, and water conveyance.

3.1. Geology

The Rio Grande valley in New Mexico is composed of a sequence of connected basins and constrictions that are bordered by tilted fault blocks of the Basin and Range physiographic province (**Figure 3.1**). It has a complex geologic and geomorphic history (Smith et al., 2001; Belcher, 1975) with periods of mountain formation (Sangre de Christo, Sandia, San Cristobal, Calballo), faulting, volcanism and sediment deposition (Santa Fe Formation). A recent aeromagnetic survey of two areas of the Albuquerque basin revealed many faults in the valley alluvium that were not detected by traditional mapping methods (Grauch, 2001; Kelley, 1977, p. 43).

The Rio Grande south of Cochiti Dam flows through three structural basins (Española, Albuquerque-Belen, and San Marcial) (Woodward et al., 1975). The limits of each basin appear to reflect geologic controls of significance (Figure 3.1). For example there is a major constriction of the Rio Grande valley at San Felipe. There are several faults projected through the narrows (Kelley, 1977), but the obvious control is a volcanic talus slope on the right bank and clay banks on the left (Culbertson and Dawdy, 1964). Another significant narrowing of the valley occurs at Isleta where the river is confined between volcanics on the west and Santa Fe Formation on the east. According to Kelley (1977), this marks the northern extent of the Belen fault.

Both at San Felipe and Isleta, the longitudinal river profile changes. At San Felipe, the gradient steepens and it is probable that bedrock is preventing incision at this location. At Isleta, the gradient is less below the diversion, but the reason is not obvious.

The major geologic control on the river extends from Belen to Socorro. This is an active uplift with its apex at about San Acacia. Earthquakes occur along the Rio Grande rift, as could be expected, and nearly all occur from Albuquerque to Socorro with the majority occurring between Belen to Socorro (Sanford et al., 1979).

In the Rio Grande valley, rapid uplift has been measured between Belen and Socorro (Reilinger and Oliver, 1976; Reilinger et al., 1980). The uplift, which was detected by re-leveling of geodetic survey lines, is a roughly elliptical dome with its center about 15 miles north of Socorro. The maximum uplift near the center is about 20 cm (about 8 inches), as measured between 1911 and 1951 (5 mm/year). Reilinger and others (1980) suggested that the uplift is caused by expansion of the Socorro magma body (Sanford et al., 1977). The Rio Grande flows across the uplift roughly along its major axis.

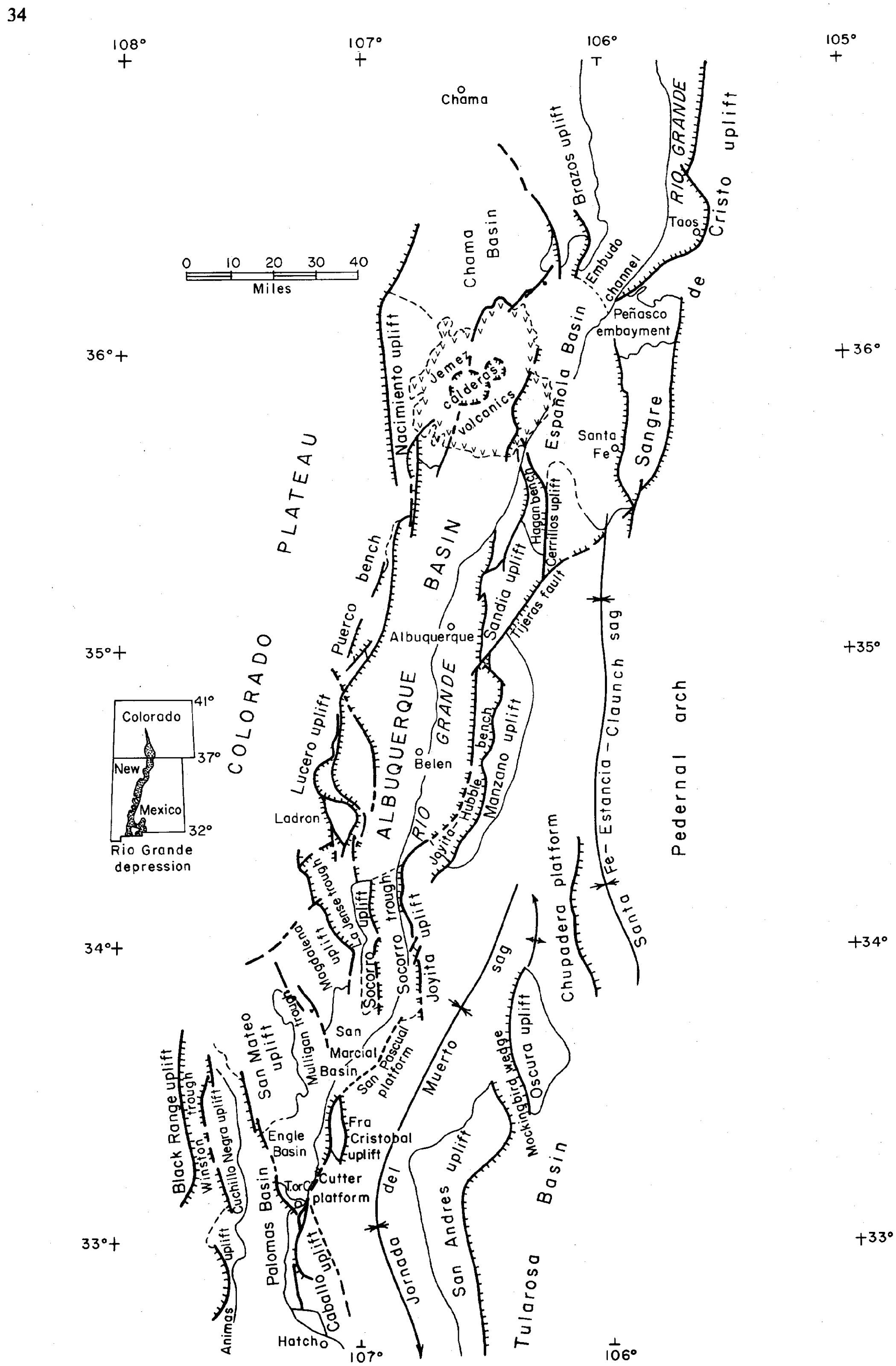


Figure 3.1. Tectonic map of the Rio Grande Rift system in New Mexico showing the locations of the structural basins and associated zones of uplift (Kelley, 1977).

The longitudinal profile of the Middle Rio Grande shows a large convexity in the uplifted area (Figure 2.10). A more detailed profile showing aggradation and degradation between 1917 and 1972 before Cochiti Dam came into operation clearly illustrates the zone of uplift and the resulting convexity of the Rio Grande profile between Belen and Socorro (**Figure 3.2**).

Major deposition by the 1929 flood from Rio Puerco and Rio Salado appears on the 1936-1938 profile as a small convexity on the larger convexity from the mouth of the Rio Puerco to San Acacia (Figure 3.2). This convexity was removed by 1944, probably by Rio Grande floods in 1937 and 1941. Therefore, local deposition is not the cause of the convexity in the Rio Grande thalweg profile. The fact that the center and areal expanse of the convexity almost perfectly coincides with the uplift indicates that it is caused by the uplift (Ouchi, 1985). In addition, there are terraces in the central area of uplift that display marked upward convexity.

Aggradation, which has been a problem in the Middle Rio Grande, is affected by the uplift. There was aggradation between 1917 and 1972 upstream of the Rio Puerco. Aggradation can be explained by the slope reduction of the upstream side of the uplift (Figure 3.2). The reduced discharge of the Rio Grande and increased sediment supply from tributaries since the late 19th century probably accelerated this aggradation (Happ, 1948). In the reach from Lemitar to the downstream limit of the uplift, sediment derived from the uplift has caused aggradation (Figure 3.2).

In summary, there was aggradation on the upstream limb of the uplift between 1936 and 1972. There was both aggradation and degradation on the downstream limb of the uplift during that period. These observations agree well with the results of experimental studies of the effect of uplift on braided streams (Ouchi, 1985). However, modification of the channel by dredging and channelization has significantly altered the natural situation.

It is probable that the Sevilleta National Wildlife Reserve exists because of the uplift downstream. The Bosque del Apache National Wildlife Reserve may also exist because of geologic controls. The narrowing of the Rio Grande valley at San Marcial is probably the result of a bedrock control similar to those at San Felipe and Isleta (Table 2.1).

The Joyita Uplift, located on the east side of the Rio Grande (Figure 3.1) affects both the topography and geology of the Rio Grande valley in Reaches 5,6 and 7 (**Figure 3.3**). The uplift, bounded on the west by the West Joyita Fault, causes a higher elevation complex of highly faulted sedimentary, volcanic, metamorphic and igneous rocks to be present on the east side of the river (Kelley, 1977). The exposed rocks are the source of both sediment and runoff that are able to traverse the much-narrowed belt of Santa Fe Formation that exists between the margin of the uplifted rocks and the Rio Grande. The reduced width of the Santa Fe Formation outcrop and the increased slope of the channels permit flood flows in the east-side tributaries to deliver sediment to the river (**Figure 3.4**). This is in contrast to the situation in Reaches 4a and 4b where the width of the Santa Fe Formation outcrop is high and very few tributaries are present because of flow infiltration into the highly permeable Santa Fe sediments (Chronic, 1987). The local geological setting, therefore, is very important with respect to sediment delivery to the Rio Grande in Reaches 5, 6 and 7.

In summary, geology has significantly affected the Rio Grande at San Felipe, Isleta, and San Marcial. The reach of river between Belen and Socorro is influenced by active deformation, but human activities have largely obscured the natural impacts. Sediment supply in Reaches 5, 6, and 7 is also significantly affected by local geology.

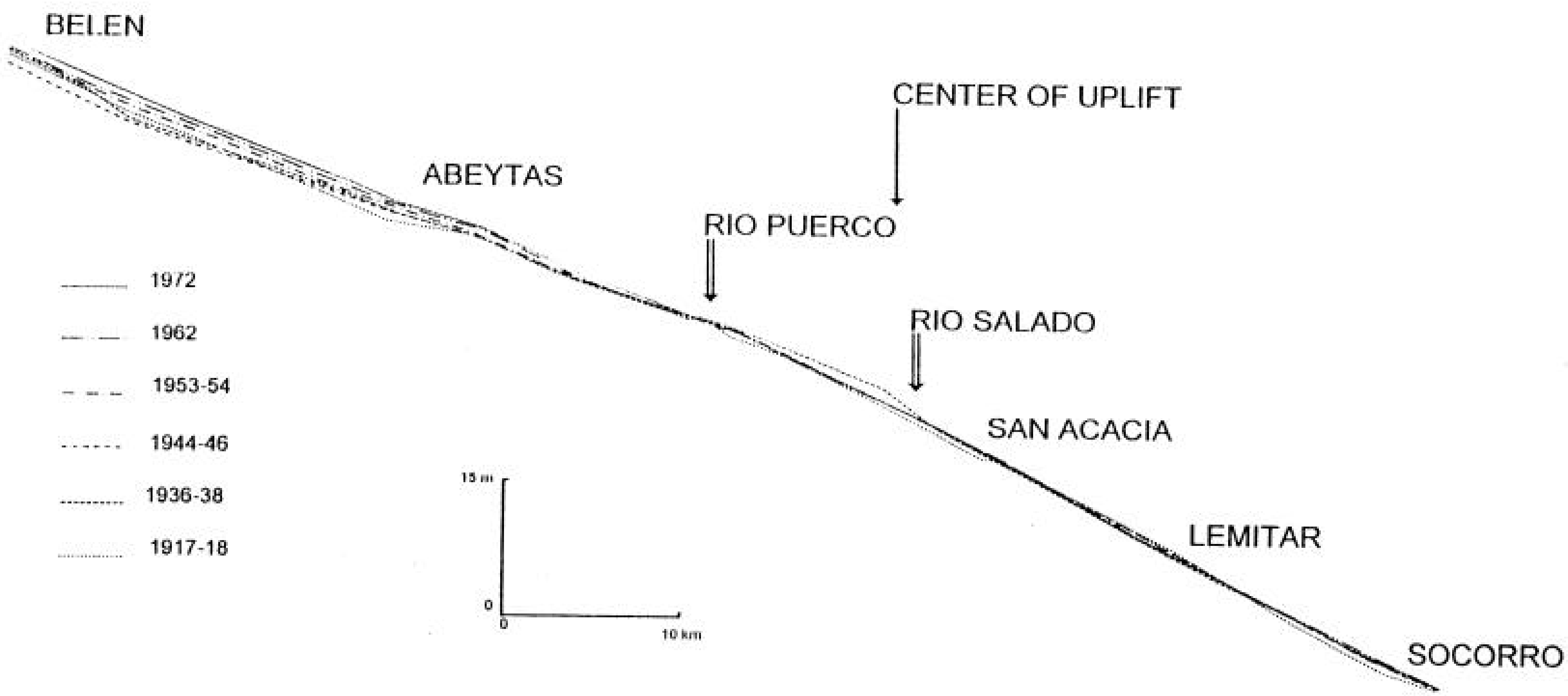


Figure 3.2. Longitudinal profiles of the Rio Grande from Belen to Soccorro (Ouchi, 1983).

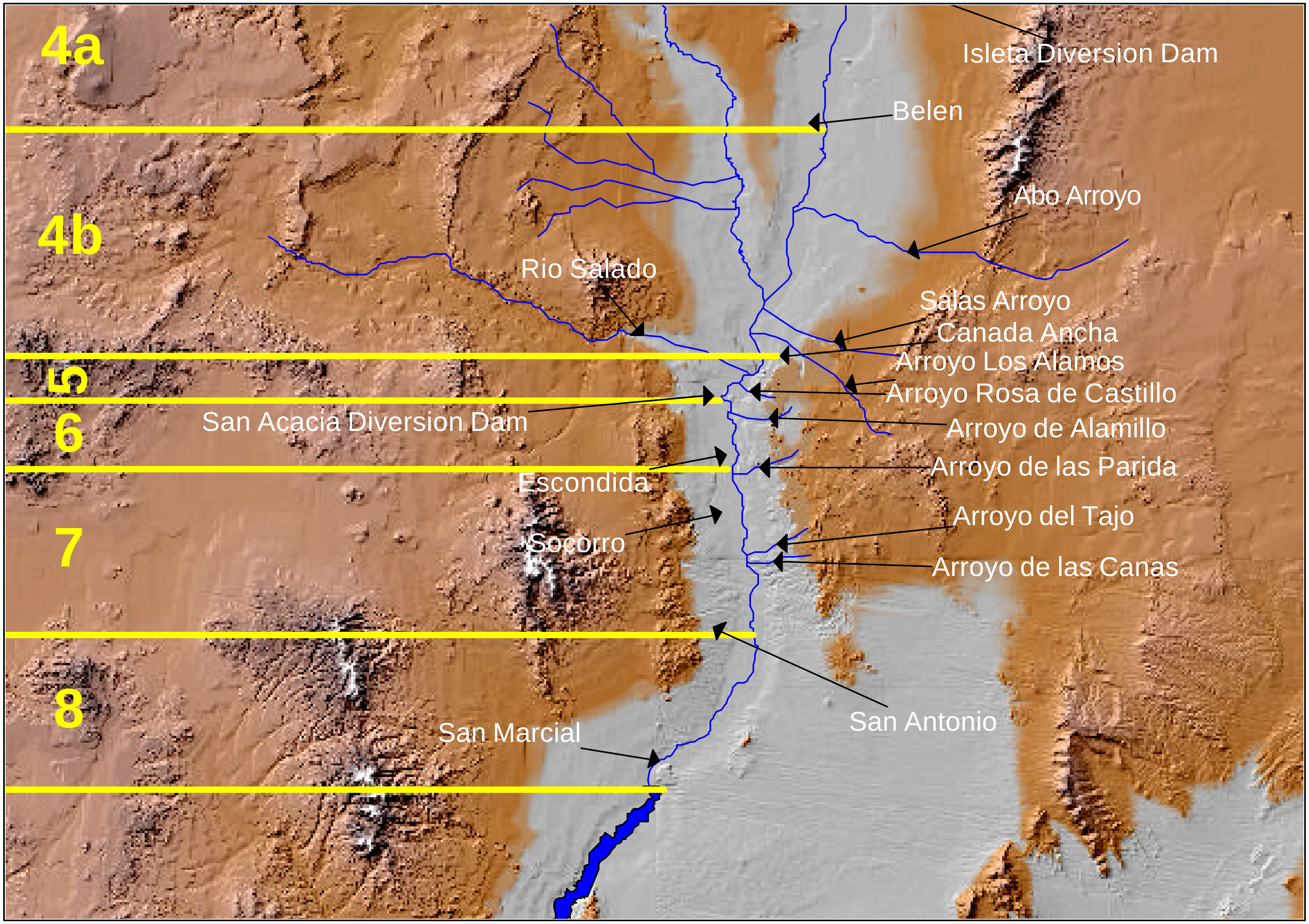


Figure 3.3. Map of the Rio Grande valley centered on Soccorro showing the effects of the Joyita Uplift on the local geology and topography, as well as the frequency of the east-side tributaries.

Figure 3.4. 1935 aerial photograph (#5925A) showing the high frequency of east-side tributary arroyos draining the Joyita Uplift in Reach 6, and delivering sediment to the Rio Grande. The reach of the river is located near Soccorro, between RM 96 and RM 102.

3.2. Hydrology

The hydrology of the Rio Grande has been significantly modified since the 1800s. The National Resources Commission (1938) reported that the natural flows in the river in the upper Rio Grande Basin in Colorado had been reduced by 40 to 60 percent by about 1890, and Jones and Harper (1998) concluded that the mean annual discharge decreased by about 60 to 70 percent from 1875 to 1925 at the del Norte gage, primarily as a result of irrigation withdrawals. In order to offset the upstream usage and to help the State of Colorado meet its downstream Compact delivery obligations, the Closed Basin-San Luis Valley Project was developed to pump water from wells to supplement the flows in the Rio Grande. Since many of the planform and size characteristics of a river are related to the discharge (Schumm, 1977), it would not be surprising if the characteristics of the river were affected by the changes in basin hydrology. In fact, in the upper basin, Jones and Harper (1998) concluded that the changed hydrology was responsible for reduced meander wavelength, increased channel sinuosity, reduction in multiple channel reaches, and increased channel stability.

A number of water storage, and flood- and sediment-control dams have been constructed in the Middle Rio Grande since the MRGCD constructed El Vado Reservoir on the Rio Chama in 1935. The San Juan-Chama Project was completed in 1971 with the construction of Heron Reservoir on the Rio Chama. The USBR imports on average (1971-1998) 96,600 acre-feet of San Juan River water annually, of which about 54,600 acre-feet is delivered to the Otowi gage (N. Shafike, pers. comm., 2001). Other reservoirs that were constructed for water supply and flood-and sediment-control purposes include: Abiquiu Reservoir on the Rio Chama (1963 by COE), Jemez Canyon Reservoir on the Jemez River (1954 by COE), Galisteo Reservoir on Galisteo Creek (1970 by COE), and Cochiti Reservoir on the Rio Grande (1975 by COE). Elephant Butte Reservoir at the downstream end of the Middle Rio Grande was constructed by the USBR in 1916. Other factors that influence the hydrology of parts of the Middle Rio Grande include the City of Albuquerque wastewater discharge to the Rio Grande that averages about 60,000 acre-feet annually, and the Low Flow Conveyance Channel (LFCC) that was completed in 1959, and that has the capacity to convey about 2,000 cfs between San Acacia and Elephant Butte Reservoir. The LFCC channel has not been operated since 1985 (Crawford et al., 1993).

In order to quantify the changes in hydrology the published records for the following gages were obtained, analyzed and evaluated:

1. Rio Grande at Otowi (Gage No.08313000; 1896-1997)

2. Rio Grande at, and below, Cochiti (Gage Nos. 08314500, 08317400; 1927-1999)

3. Rio Grande at San Felipe (Gage No. 08319000; 1927-1999)

4. Rio Grande near Bernalillo (Gage No. 08329500; 1929-1969)

5. Rio Grande at Albuquerque (Gage No. 08330000; 1942-1999)

6. Rio Grande Floodway near Bernardo (Gage No. 08332010; 1958-1999)

7. Rio Grande Floodway at San Acacia (Gage No. 08354900; 1959-1999)

8. Rio Grande at San Marcial (Gage No. 08358400; 1925-1999)

The hydrologic records were evaluated in terms of: (1) the occurrence of floods, because flood history and sequencing is likely to be very important in a river such as the Rio Grande (Baker, 1977), (2) the flood-frequency relations before and after the period of flood-control reservoir construction, since the magnitude of the floods is likely to be morphologically significant (Wolman and Miller, 1960; Wolman and Gerson, 1978), and (3) the flow durations in the pre- and post-San Juan-Chama importations because of the potential impact of the increased flows on sediment transport and channel morphology in the sand-bed reaches (Anthony and Harvey, 1991).

3.2.1. Flood Frequency

Flood-frequency curves, using a log Pearson Type III distribution, were developed for each of the gages for the pre- and post-Cochiti Reservoir construction periods using the U.S. Army Corps of Engineers HEC-FFA computer program (COE, 1992) which is based on the procedures outlined in Water Resource Council (WRC) Bulletin 17B (WRC, 1981). The pre-Cochiti flood-frequency curves for the Cochiti, San Felipe, Albuquerque, Bernardo, San Acacia, and San Marcial gages are presented in **Figures 3.5 through 3.10**, respectively. The post-Cochiti flood-frequency curves for the Cochiti, San Felipe, Albuquerque, and San Marcial gages are presented in **Figures 3.11 through 3.14**, respectively.

Table 3.1 provides a comparison of the pre- and post-Cochiti flood-frequency data for the various gages. The data show that regardless of the reach the flood-control project has reduced the magnitude of the floods for all of the listed return periods. However, it is also clear that the reduction in magnitude has been greatest for the highest return period floods. For example, at the Cochiti gage, the magnitude of the 2-year pre-Cochiti event was 6,400 cfs and in the post-Cochiti period, it is 4,480 cfs, a reduction of about 30 percent. In contrast, at the Cochiti gage, the magnitude of the 100-year pre-Cochiti event was 28,700 cfs and in the post-Cochiti period, it is 12,800 cfs, a reduction of 55 percent. The reduction for the 100-year event for the San Marcial gage is about 70 percent.

To place the peak flow reductions in perspective, it is instructive to review the relative values for the Albuquerque gage. The present 100-year discharge (12,600 cfs) was about a 10-year event in the pre-Cochiti period. Regardless of any morphological adjustments of the channel that may have occurred in response to channelization, or the presence of the upstream dams, the flood-control project significantly reduced the magnitude of the 2-year event (7,090 cfs vs. 5,410 cfs). If the channel capacity were adjusted to the 2-year event (Leopold et al., 1964; Williams, 1978; Andrews, 1980) then the flood-control project alone would have reduced the frequency of floodplain inundation, thereby affecting the ecological linkages between the channel and its floodplain (Hill et al., 1991).

3.2.2. Flood History

The annual peak flows (for the published individual gage periods of record) for the Cochiti, San Felipe, Bernalillo, Albuquerque, Bernardo, San Acacia, and San Marcial gages are presented in **Figures 3.15 through 3.21**, respectively. Identification of the 10 largest flows in the period of record at each gage enabled the sequence of floods to be evaluated, and also allowed the variations in flood frequency and peaks through the basin to be identified. In the upper portion of the project reach (Reaches 1, 2 and 3) four significant floods occurred between 1929 and 1935 with the largest being about 27,300 cfs at San Felipe in 1937 (Figure 3.16), which had a pre-dam recurrence interval of about 50 years (Figure 3.6). In 1941 and 1942 the peak flows in both years were on the order of 25,000 cfs at the Bernalillo and Albuquerque gages (Figures 3.17 and 3.18), and the recurrence interval was about 100 years on the pre-Cochiti dam

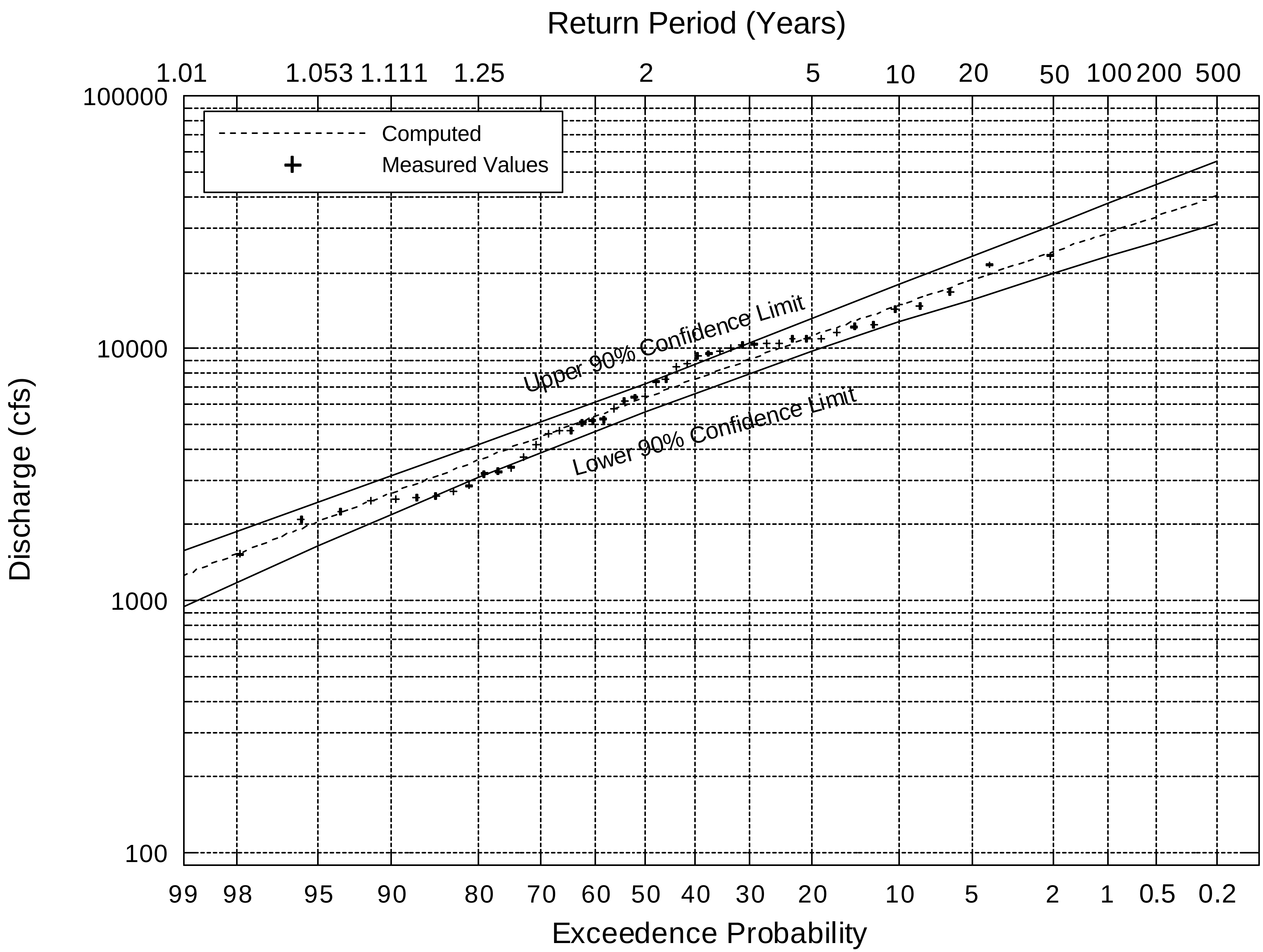


Figure 3.5. Pre-Cochiti flood-frequency curve for the Cochiti gage, based on the period of record between 1927 and 1973.

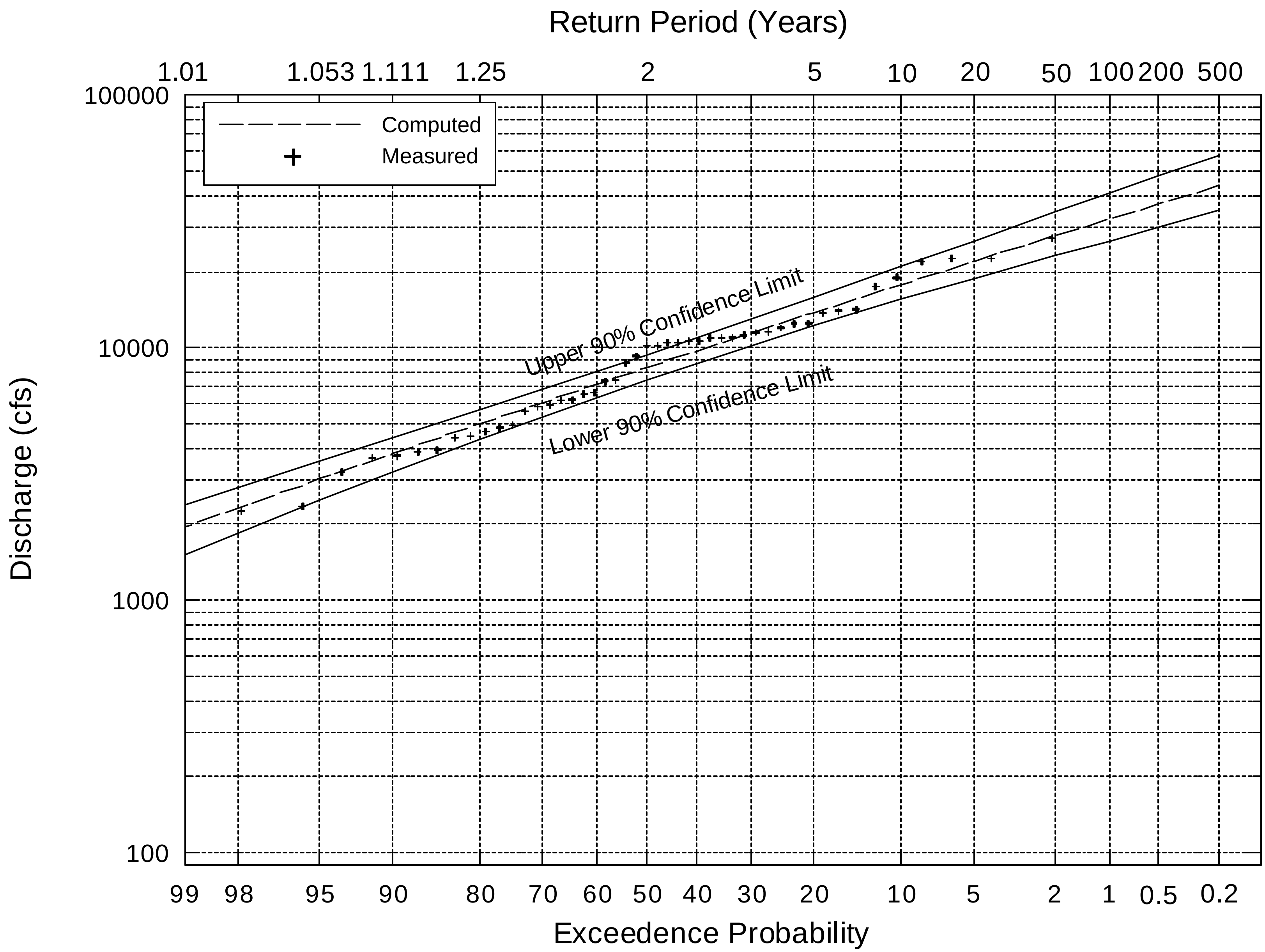


Figure 3.6. Pre-Cochiti flood-frequency curve for the San Felipe gage, based on the period of record between 1927 and 1973.

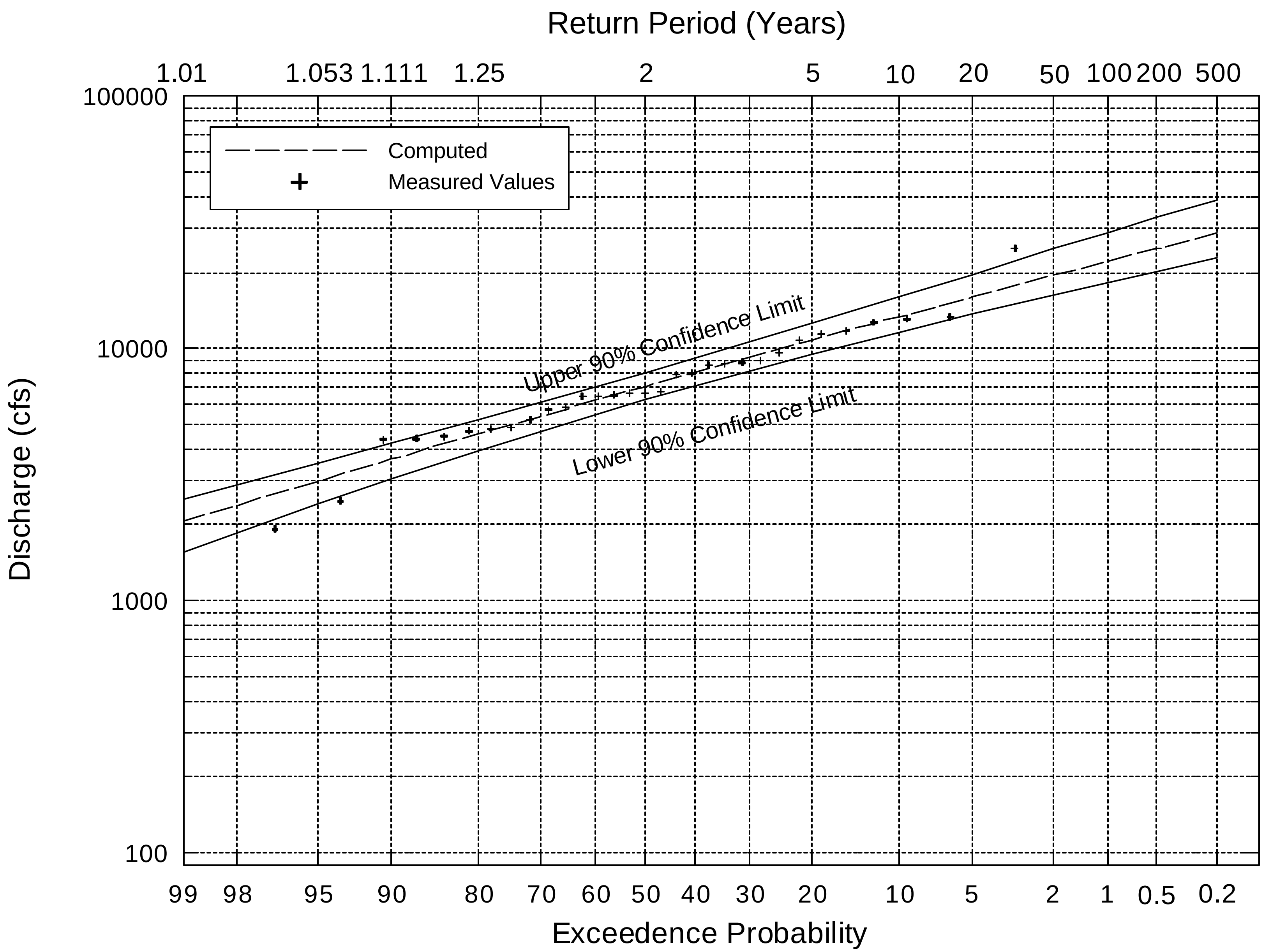


Figure 3.7. Pre-Cochiti flood-frequency curve for the Albuquerque gage, based on the period of record between 1942 and 1973.

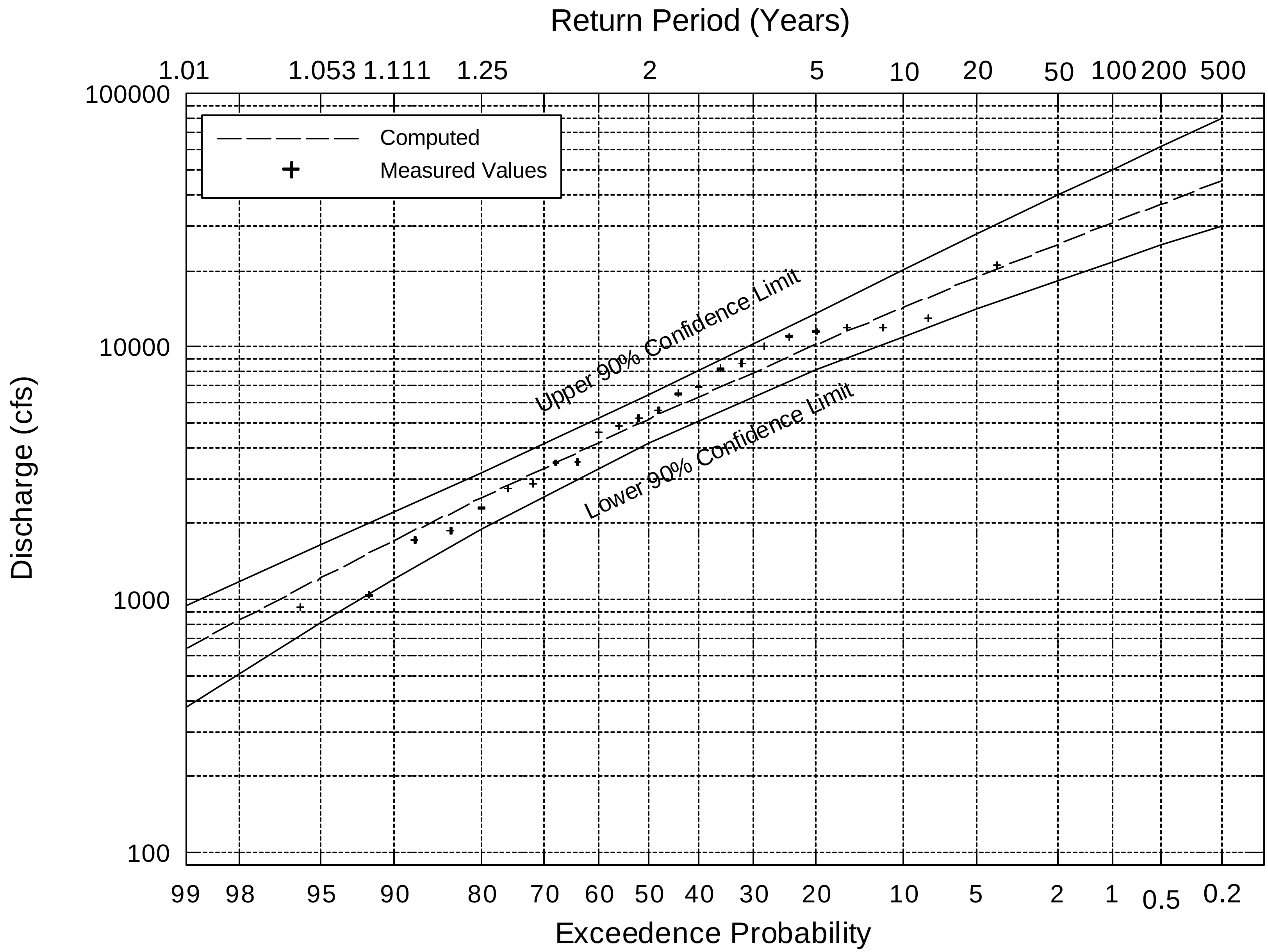


Figure 3.8. Pre-Cochiti flood-frequency curve for the Bernardo gage, based on the period of record between 1929 and 1973.

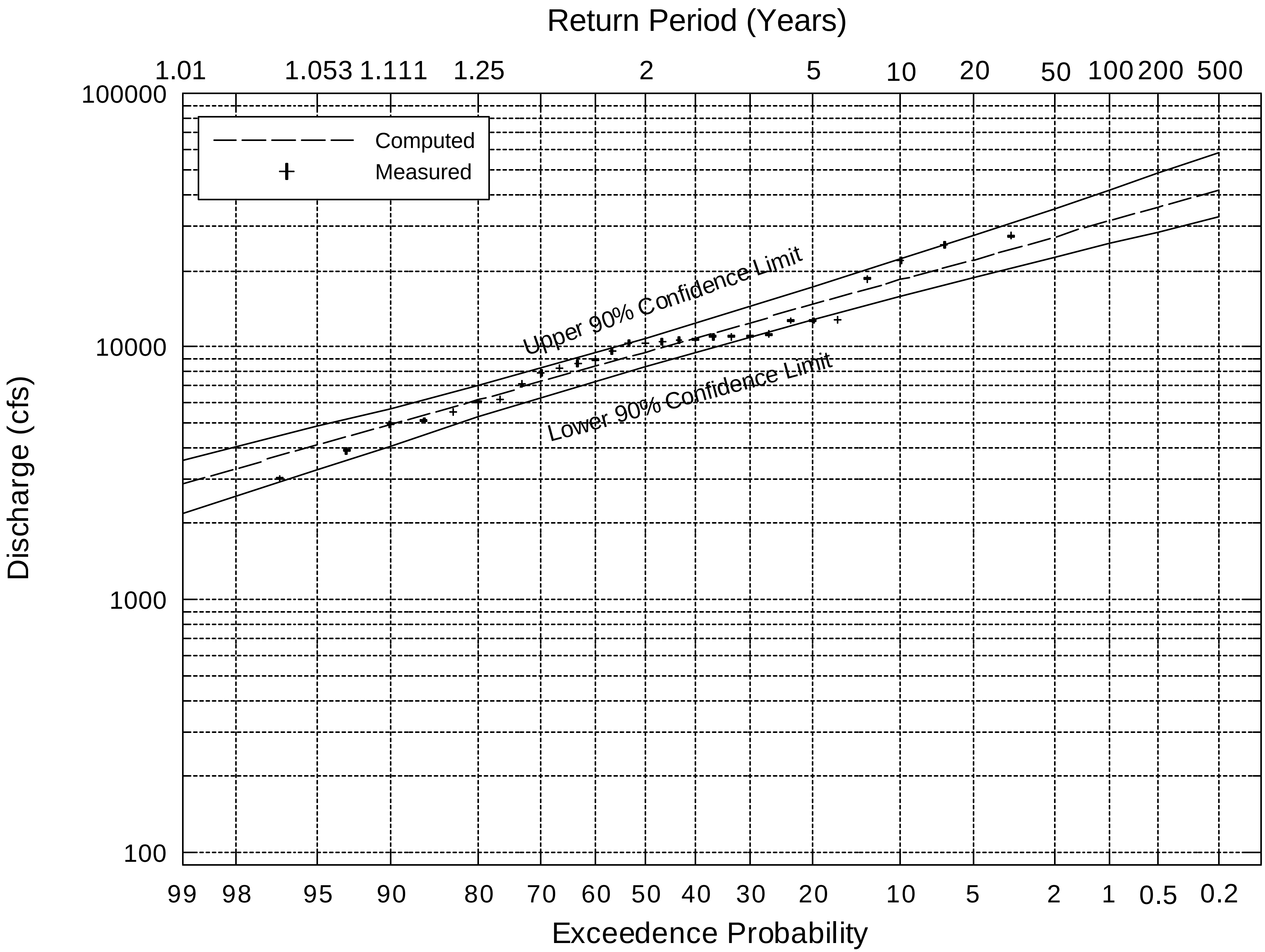


Figure 3.9. Pre-Cochiti flood-frequency curve for the San Acacia gage, based on the period of record between 1936 and 1973.

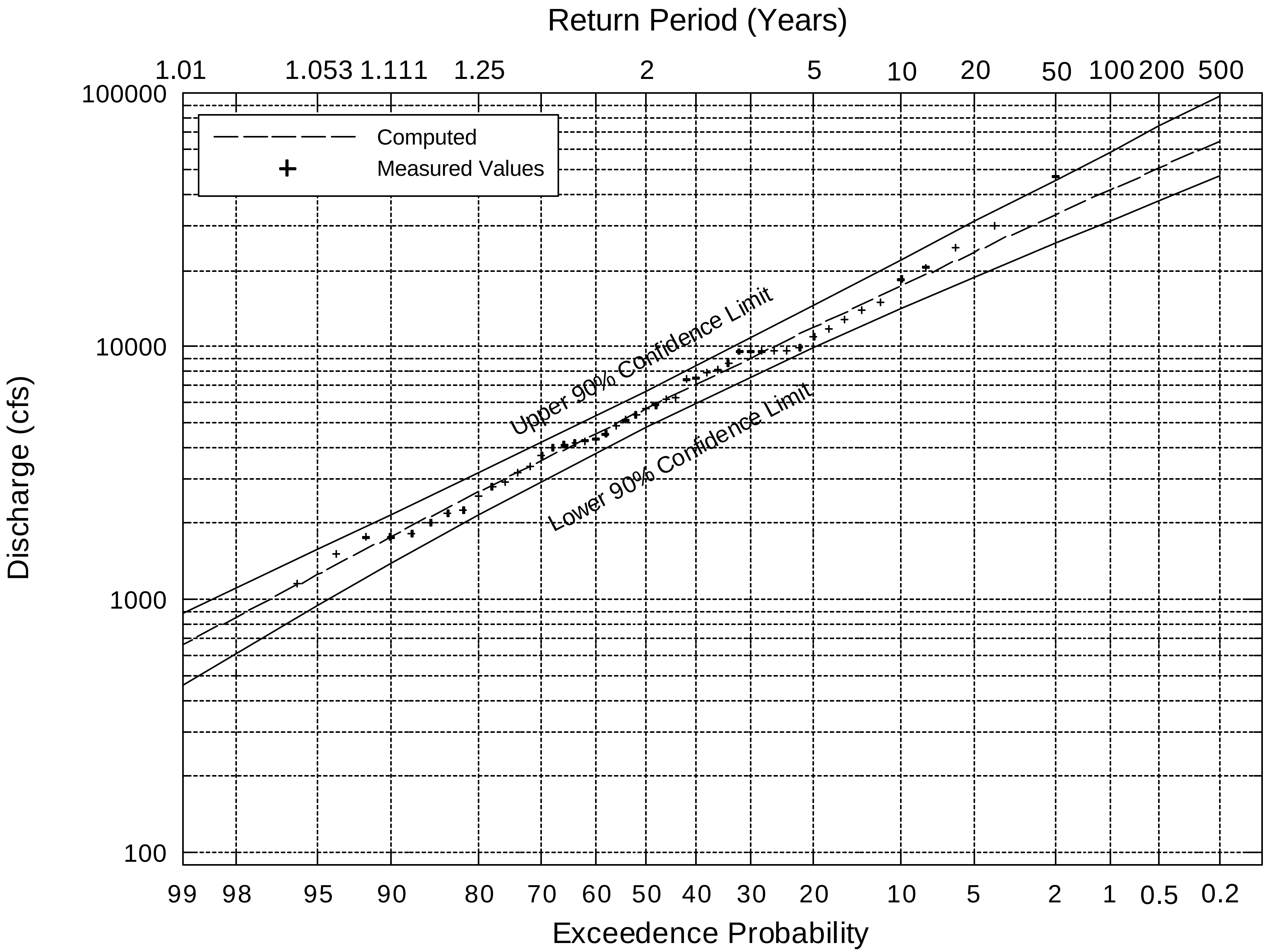


Figure 3.10. Pre-Cochiti flood-frequency curve for the San Marcial gage, based on the period of record between 1925 and 1973.

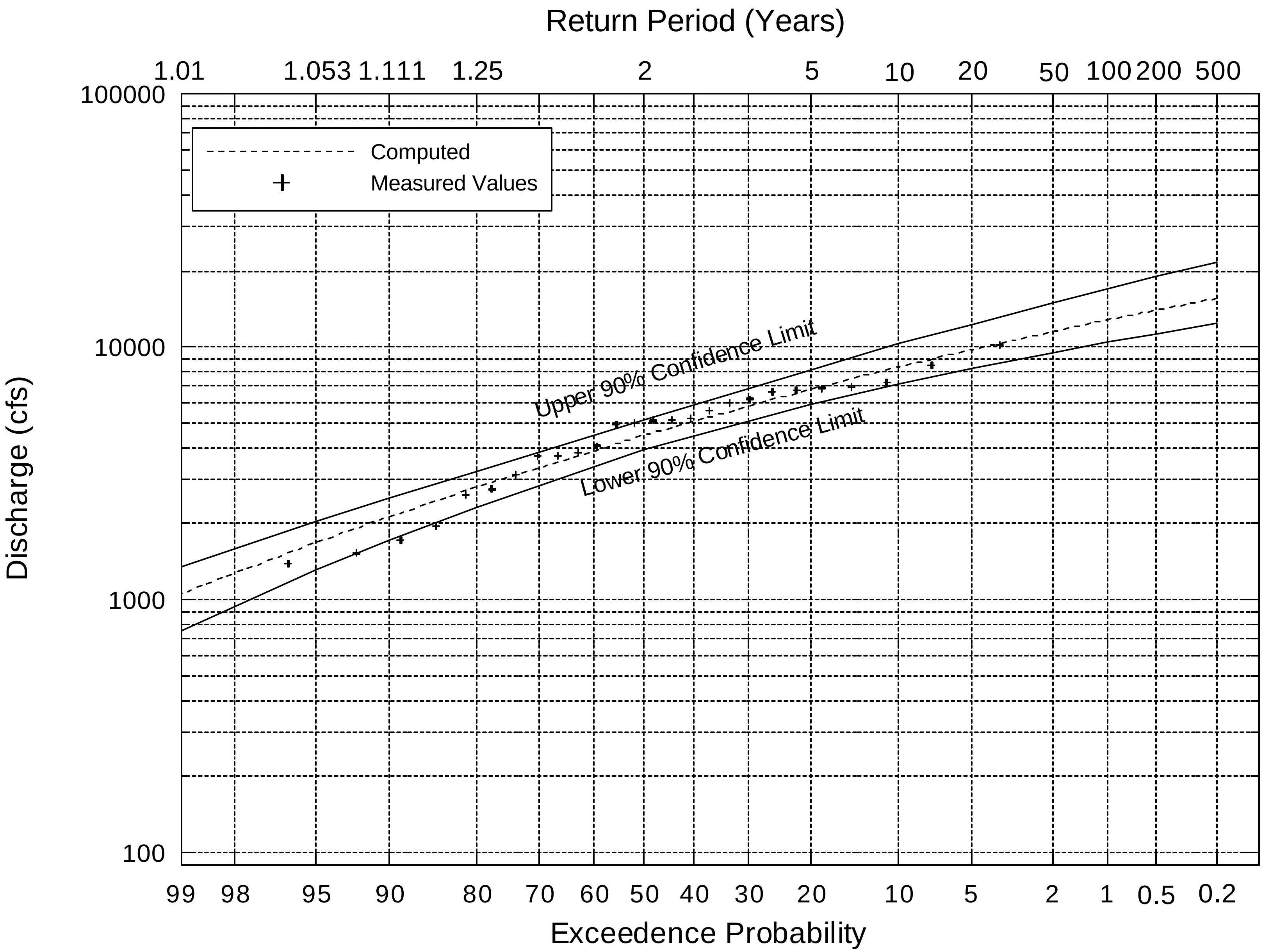


Figure 3.11. Post-Cochiti flood-frequency curve for the Cochiti gage, based on the period of record between 1974 and 1999.

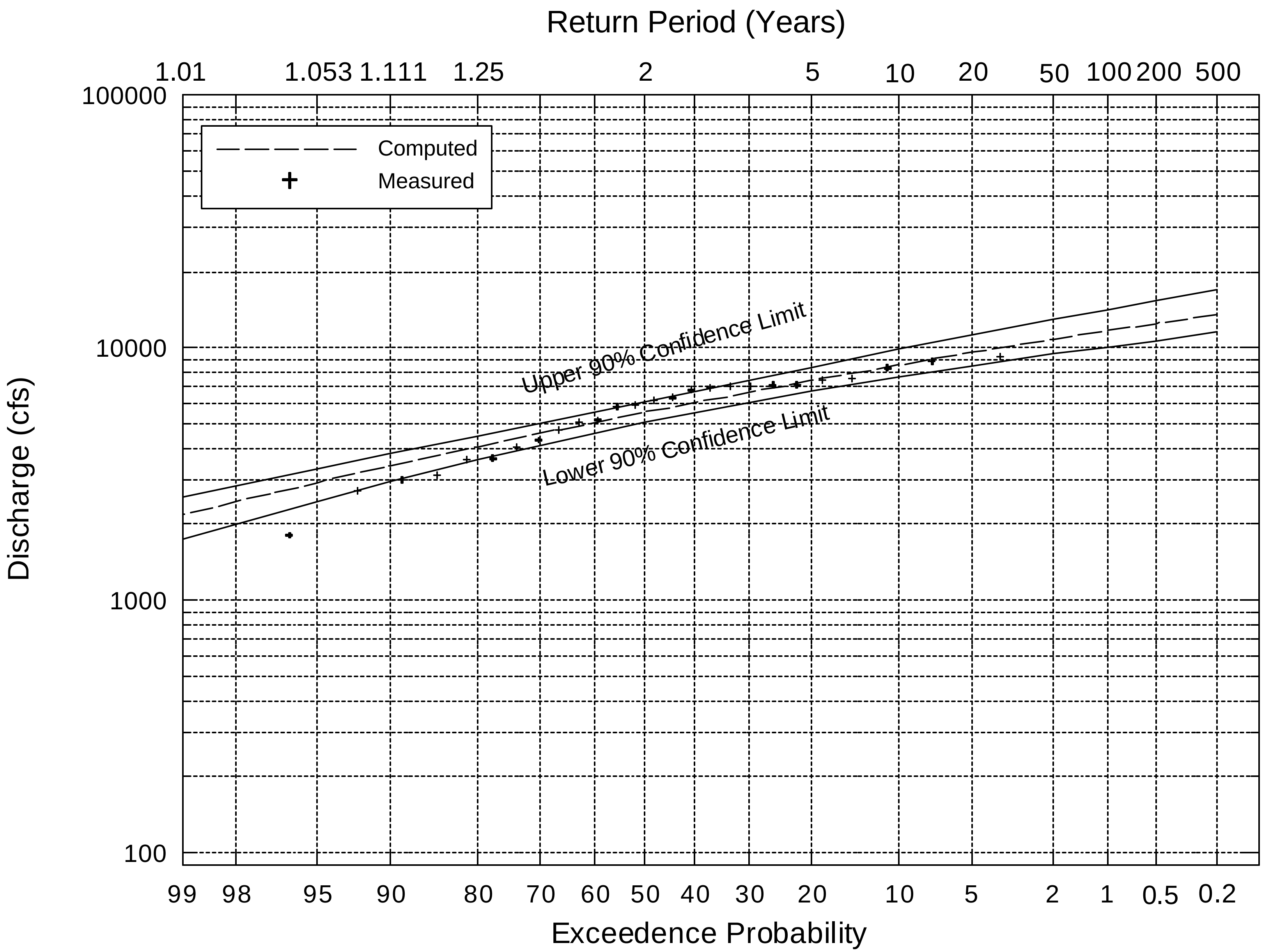


Figure 3.12. Post-Cochiti flood-frequency curve for the San Felipe gage, based on the period of record between 1974 and 1999.

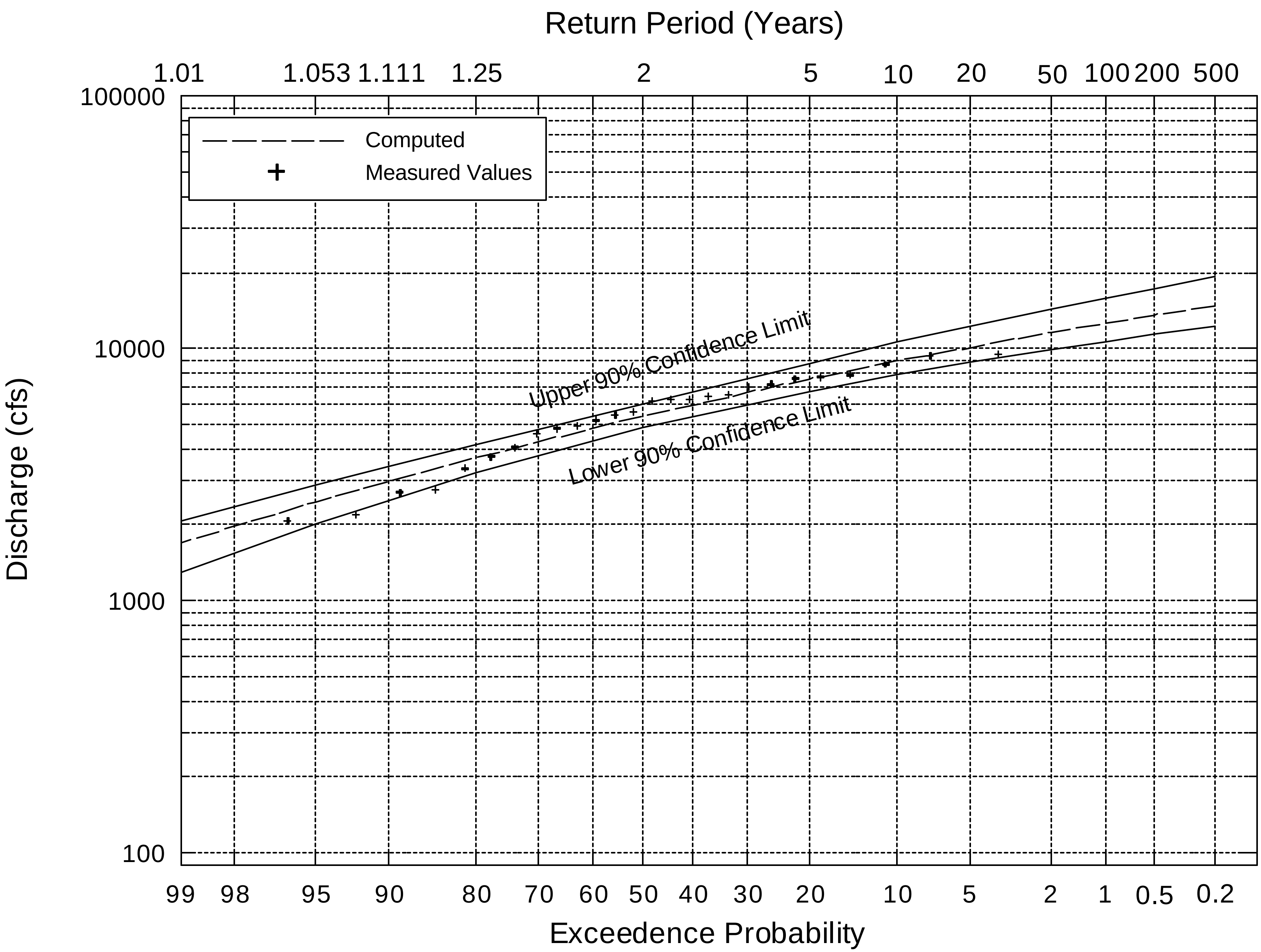


Figure 3.13. Post-Cochiti flood-frequency curve for the Albuquerque gage, based on the period of record between 1974 and 1999.

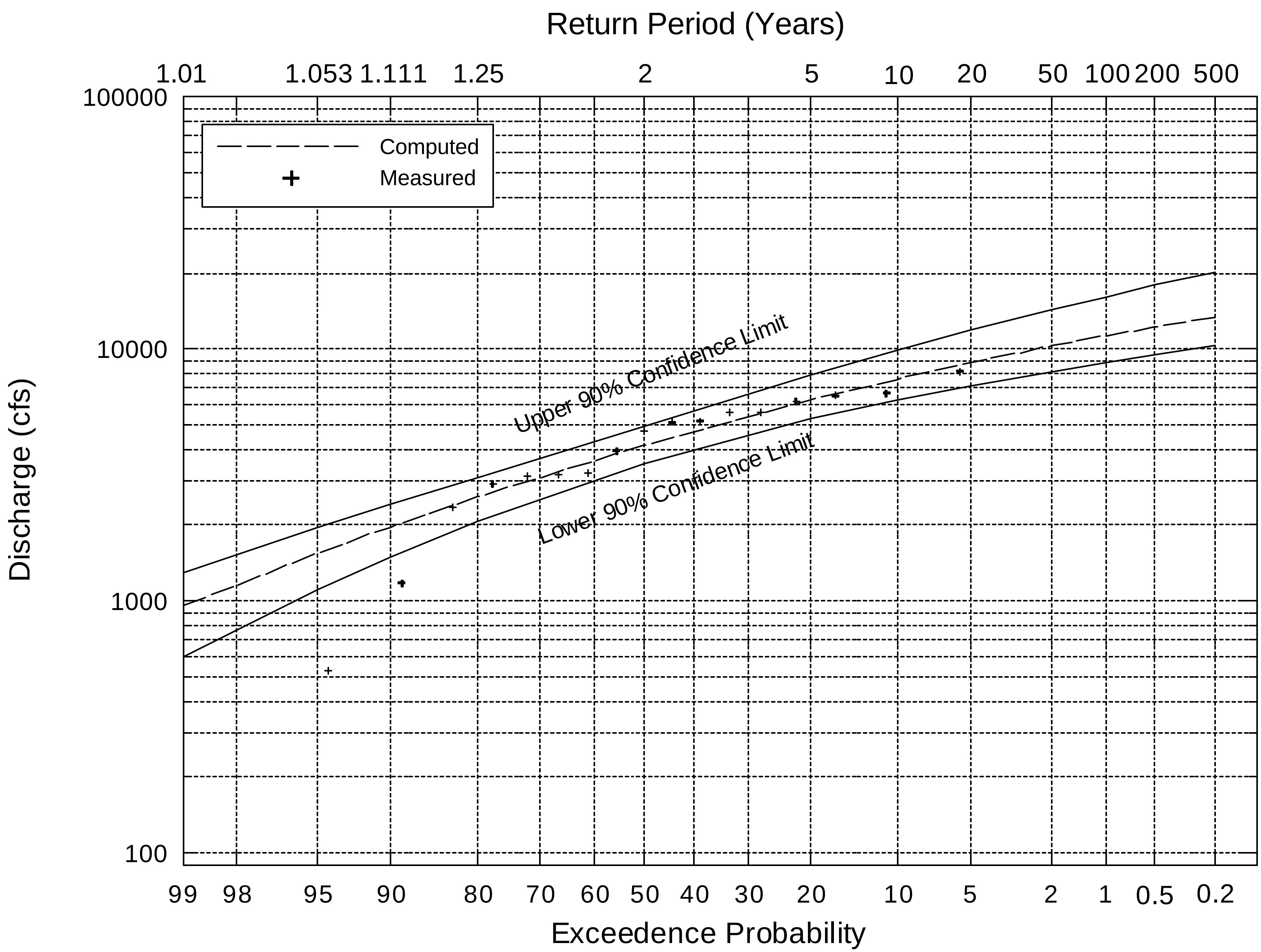


Figure 3.14. Post-Cochiti flood-frequency curve for the San Marcial gage, based on the period of record between 1974 and 1999.

Table 3.1. Peak flow hydrology (cfs).						
	Return Period (yrs)					
	2-	5-	10-	20-	50-	100-
Cochiti (1926-1999)						
Pre-1973	6,400	11,200	14,900	18,700	24,200	28,700
Post-1973	4,480	6,830	8,350	9,770	11,500	12,800
San Felipe (1927-1999)						
Pre-1973	8,370	13,800	17,800	22,000	27,700	32,300
Post-1973	5,560	7,430	8,560	9,580	10,800	11,700
Albuquerque (1942-1999)						
Pre-1973	7,090	10,800	13,400	16,000	19,500	22,200
Post-1973	5,410	7,600	8,940	10,100	11,600	12,600
Bernardo (1937-1964)						
Pre-1973	5,180	10,200	14,300	18,800	25,400	30,900
Post-1973						
San Acacia (1936-1969)						
Pre-1973	9,510	14,700	18,400	22,100	27,300	31,400
Post-1973						
San Marcial (1925-1991)						
Pre-1973	5,680	11,900	17,300	23,600	33,200	41,500
Post-1973	4,160	6,290	7,610	8,810	10,300	11,300

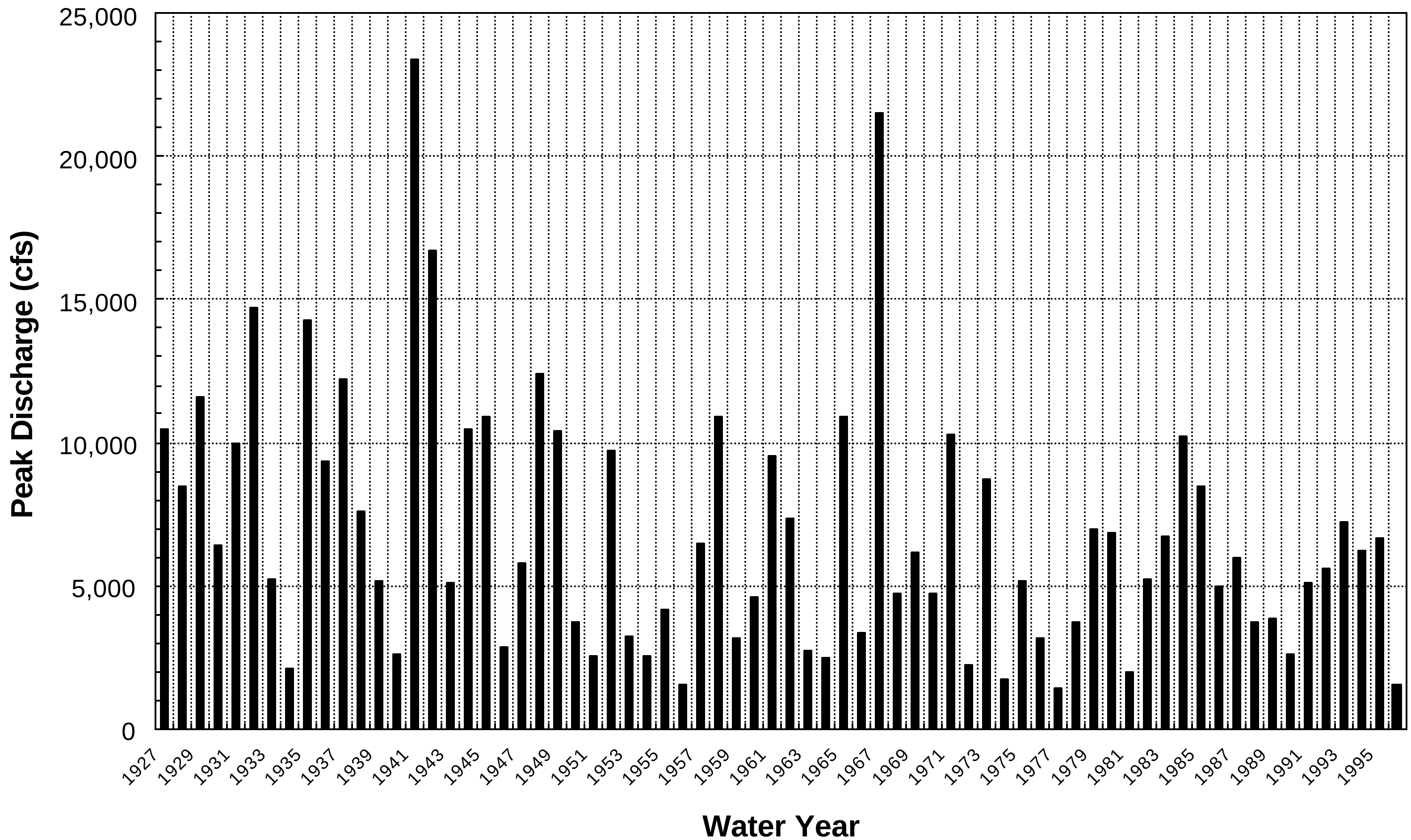


Figure 3.15. Annual maximum flood peaks for the period of record for the Cochiti gage. The data represent two separate gage locations that were necessitated by construction of Cochiti Dam.

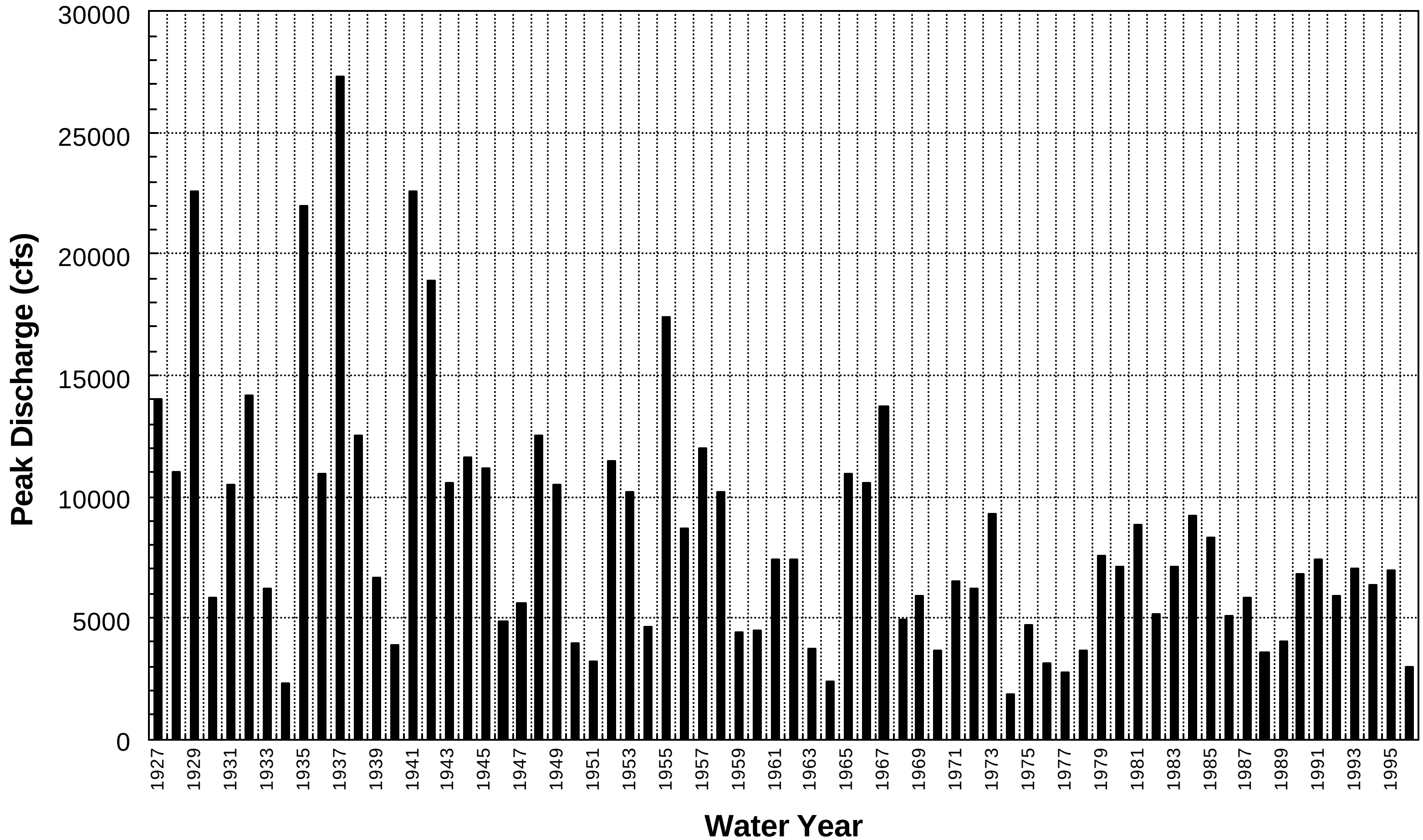


Figure 3.16. Annual maximum flood peaks for the period of record for the San Felipe gage.

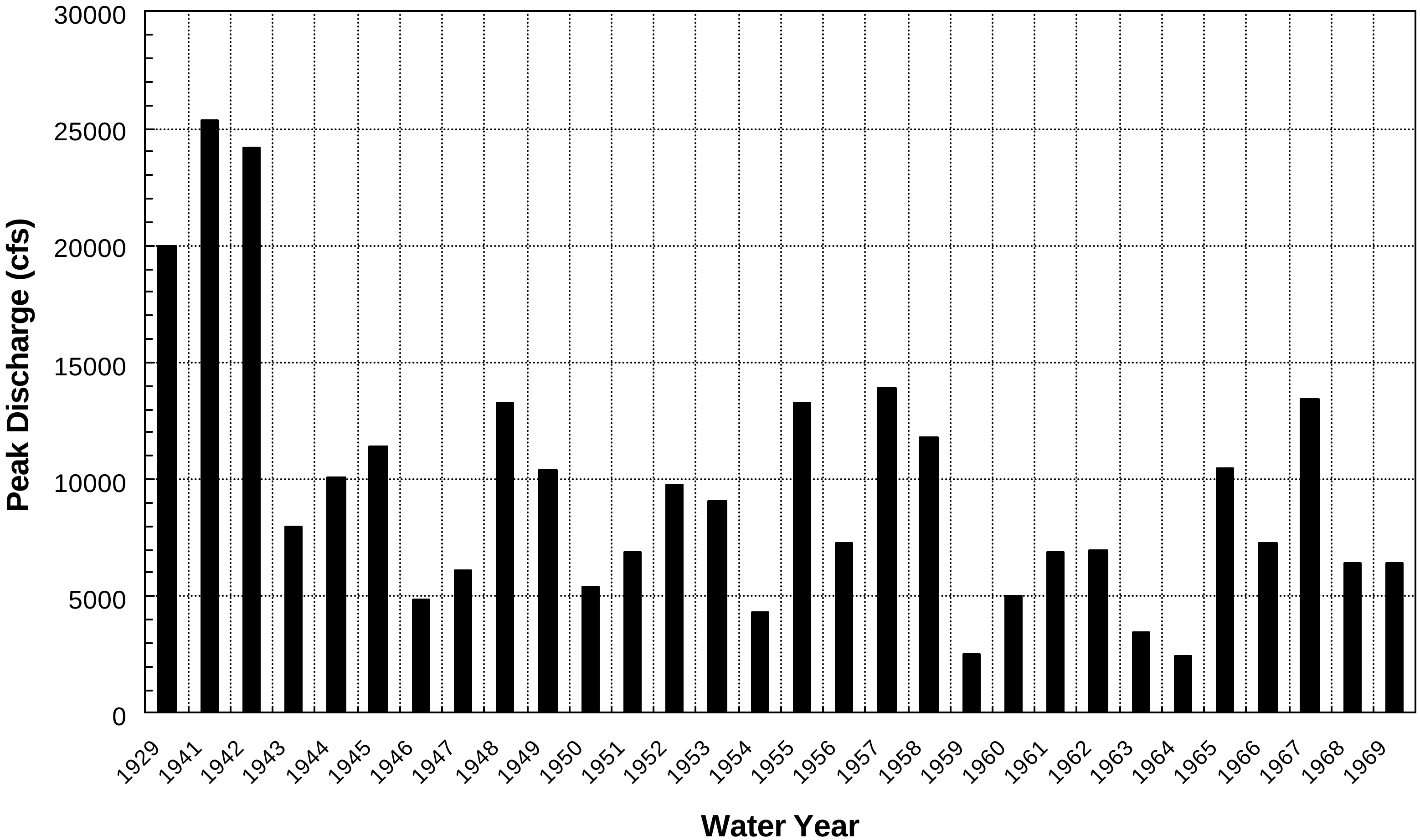


Figure 3.17. Annual maximum flood peaks for the period of record for the Bernalillo gage.

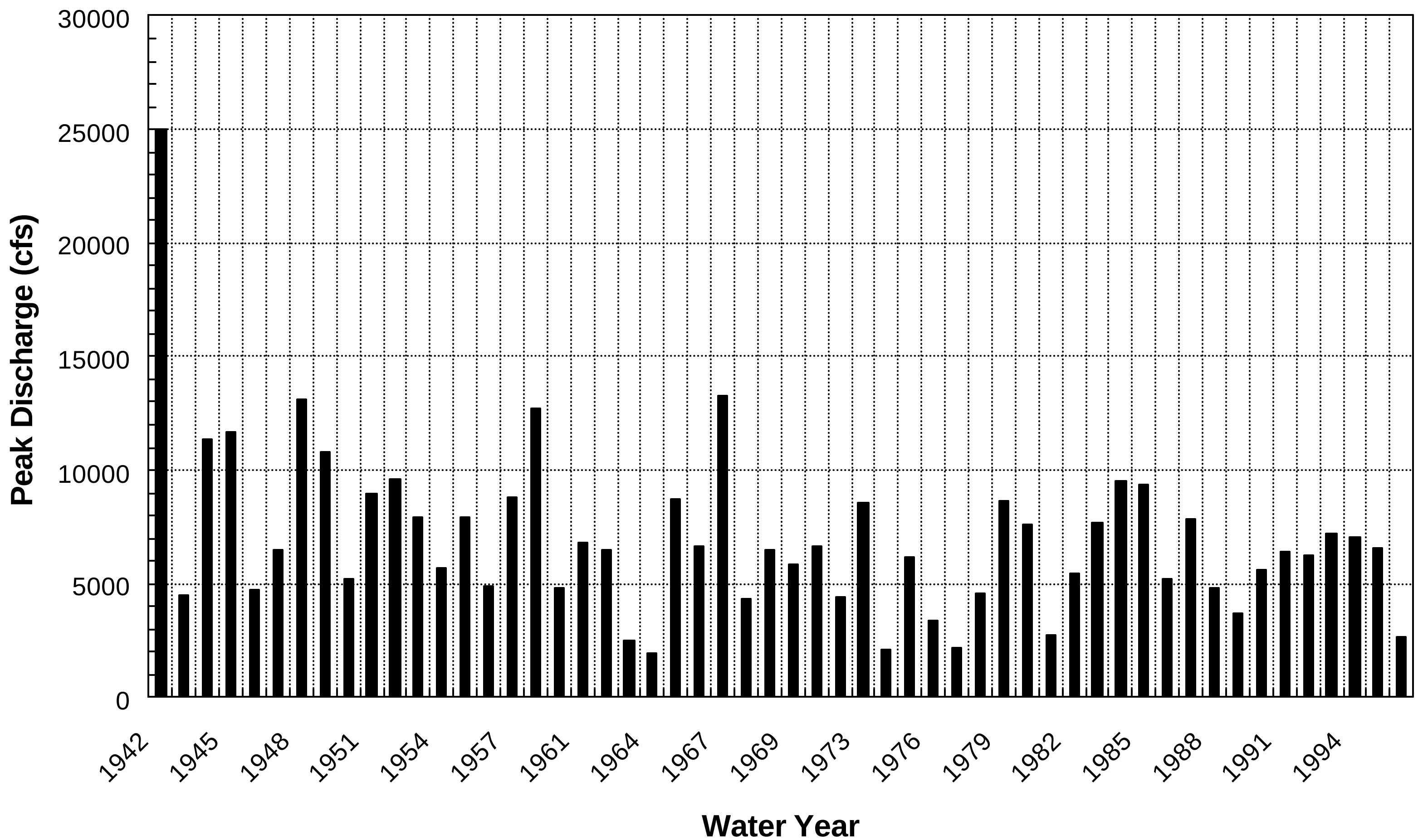


Figure 3.18. Annual maximum flood peaks for the period of record for Albuquerque gage.

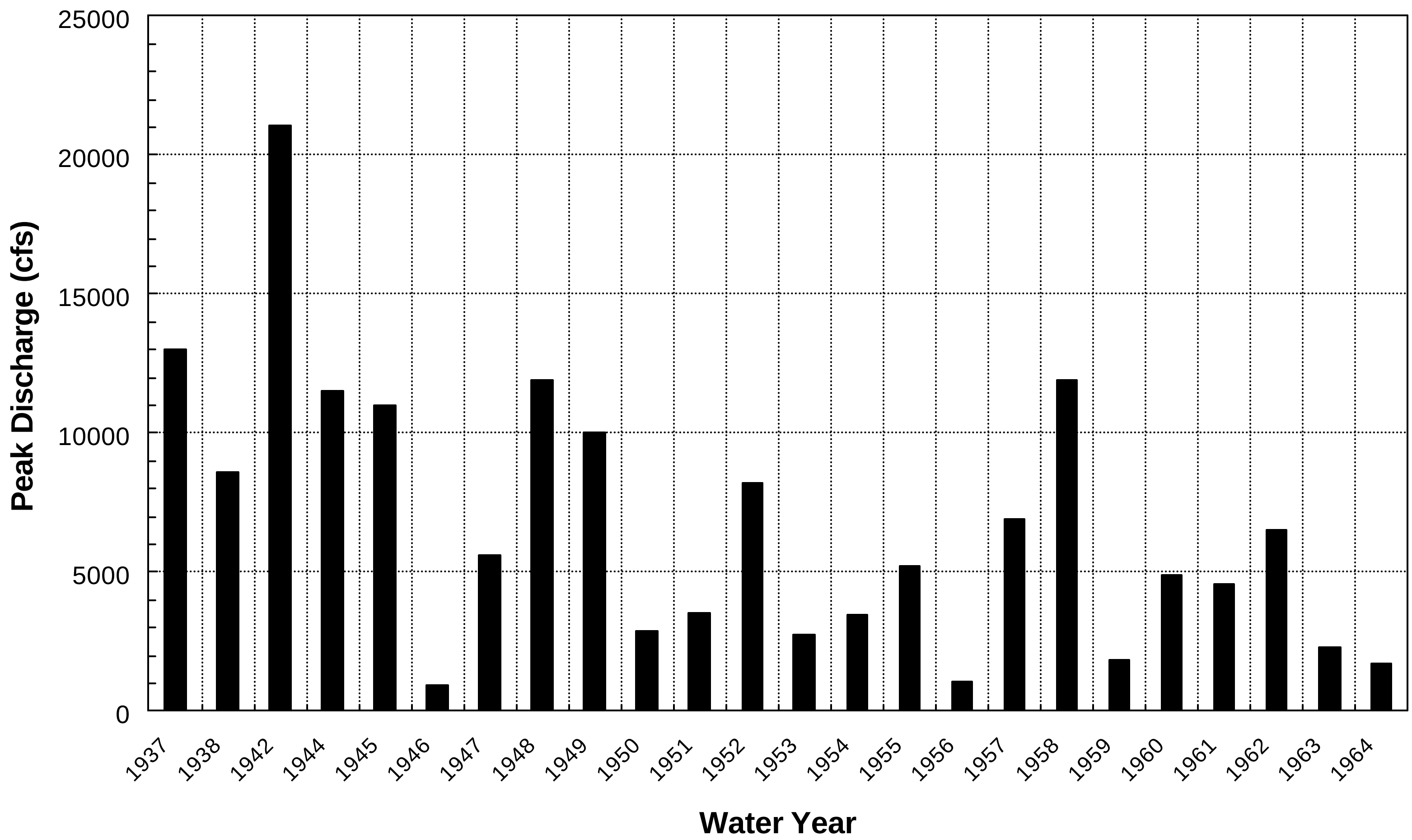


Figure 3.19. Annual maximum flood peaks for the period of record for Bernardo gage.

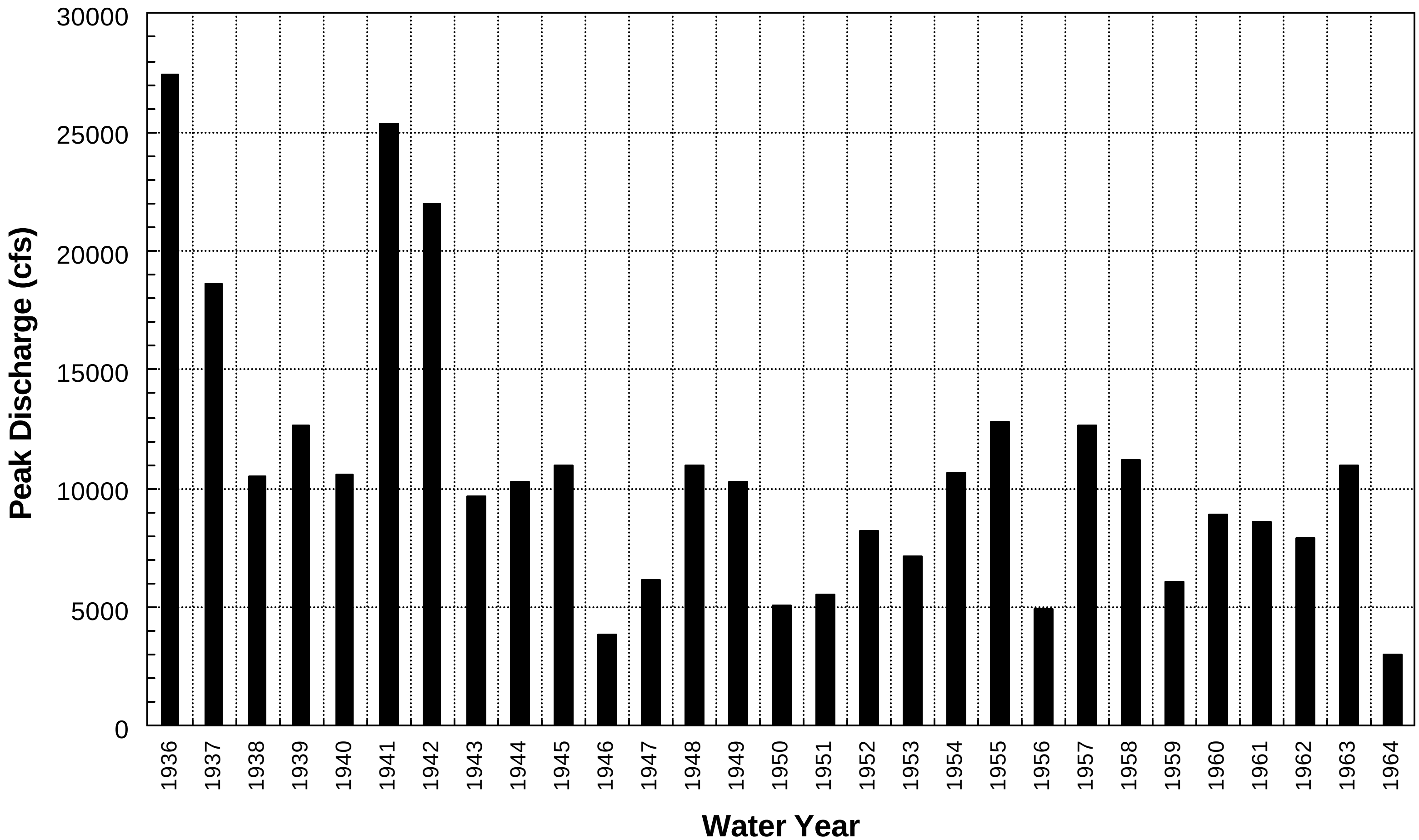


Figure 3.20. Annual maximum flood peaks for the period of record for San Acacia gage.

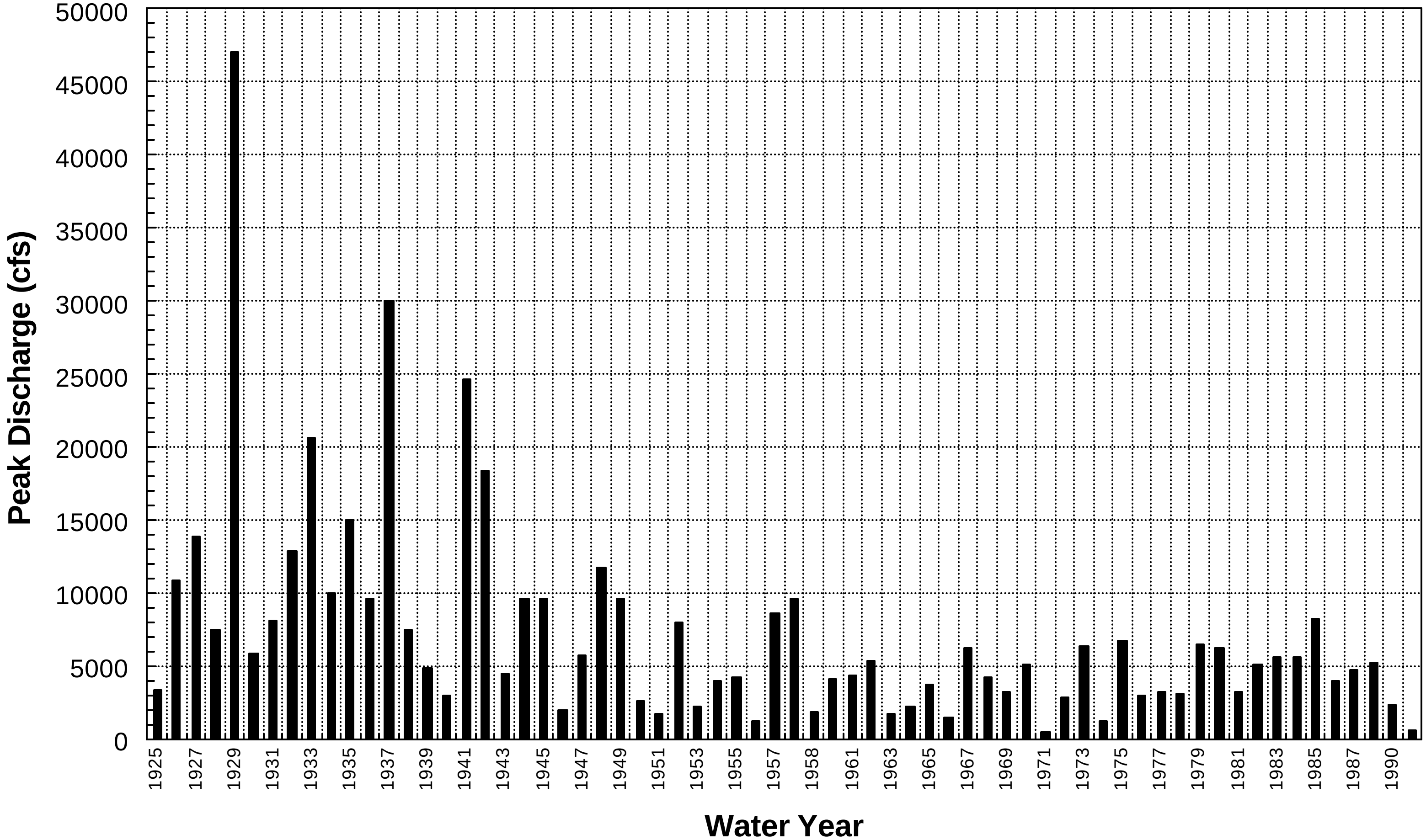


Figure 3.21. Annual maximum flood peaks for the period of record for San Marcial gage.

frequency curve (Figure 3.7). A number of lesser flood flows occurred in the late 1940s and the middle 1950s (1955 - 17,400 cfs at San Felipe), at which time the COE began the construction of the flood- and sediment-control reservoirs. It is likely that the relatively frequent large floods in the late 1920s and 1930s were morphologically significant, especially since they occurred in a general drought period in the western United States. Aerial photographs of the river in the Albuquerque area taken in 1938 suggest that the river had been significantly perturbed, which would be a similar response to drought period floods during the same timeframe in other western rivers (Schumm and Lichty, 1963). Since the upstream dams were built, the highest discharges at the Albuquerque gage have been 9,500 cfs (1984) and 9,370 cfs (1985), which had recurrence intervals on the pre-dam frequency curve of between 2 and 5 years (Figure 3.13).

In the lower reaches of the river (Reaches 5, 6, 7 and 8), the flood record reveals some interesting differences from that of the upper river. At the San Marcial Gage (Figure 3.21), the flood of record occurred in 1929 (47,000 cfs), and it had a recurrence interval on the pre-dam (Cochiti) frequency curve of about 100 years (Figure 3.10). Significant flooding and sediment deposition occurred during this event (Happ, 1948). The same flood at Bernalillo had a peak discharge of 20,000 cfs (50-year recurrence interval), which indicates that significant flows were introduced to the Rio Grande by the Rio Puerco and Rio Salado (Happ, 1948). Large floods occurred in the lower reaches in 1932, 1933, 1935, 1937 and 1938, and the events of 1937 (30,000 cfs at San Marcial) and 1938 were contributed to by the Rio Puerco and the Rio Salado. The large and long duration floods of 1941 (24,600 cfs) and 1942 (18,400 cfs), in combination with those of the 1930's had significant impacts on sediment transport, sediment deposition and changes in channel morphology in the lower reaches of the river (Happ, 1948). Several channel avulsions were reported in Reach 8 during the 1937 flood (Happ, 1948). No major floods have occurred in the lower reaches since the upstream dams and reservoirs were constructed.

Review of the flood flow record at the various gages indicates that the late 1920s and the 1930s and the early 1940s were periods of large and frequent floods throughout the Middle Rio Grande, and available photographic and survey data (Happ, 1948) indicate that the river responded to those floods by depositing large volumes of sediment and changing course and location at a number of sites. Since the sediment and flood-control dams were constructed between the late 1950s and mid 1970s there have been very few floods of any significance, and hence the river disturbance regime associated with large and frequent floods no longer occurs. The lack of morphologically significant floods is coupled with the introduction of exotic plant species, such as tamarisk and Russian olive, whose extensive roots provide effective cohesion, and hence shear strength, to essentially cohesionless sands (Smith, 1976; Gray and Leiser, 1989; MEI, 1996). In addition, extensive river training measures have been installed in all of the reaches; therefore, it is not surprising that the river is remarkably stable at the present time.

3.2.3. Flow Durations

Flow-duration curves were developed from the mean daily flow record at the individual gages for the pre- and post-San Juan-Chama water importation periods. Flow-duration curves were developed for the Otowi gage for three different periods (**Figure 3.22**), pre-El Vado Reservoir (1896-1934), post -El Vado Reservoir to pre-Abiquiu Reservoir (1935-1962), and post-Heron Reservoir (1971-1997). The individual flow-duration curves demonstrate the impact of the imported flows (about 97,000 acre-feet annually), especially beyond the 30 percent exceedence value (the value that is equaled or exceeded 30 percent of the time). The flow-duration curves also show that the upstream reservoirs also provided some measure of flood control.

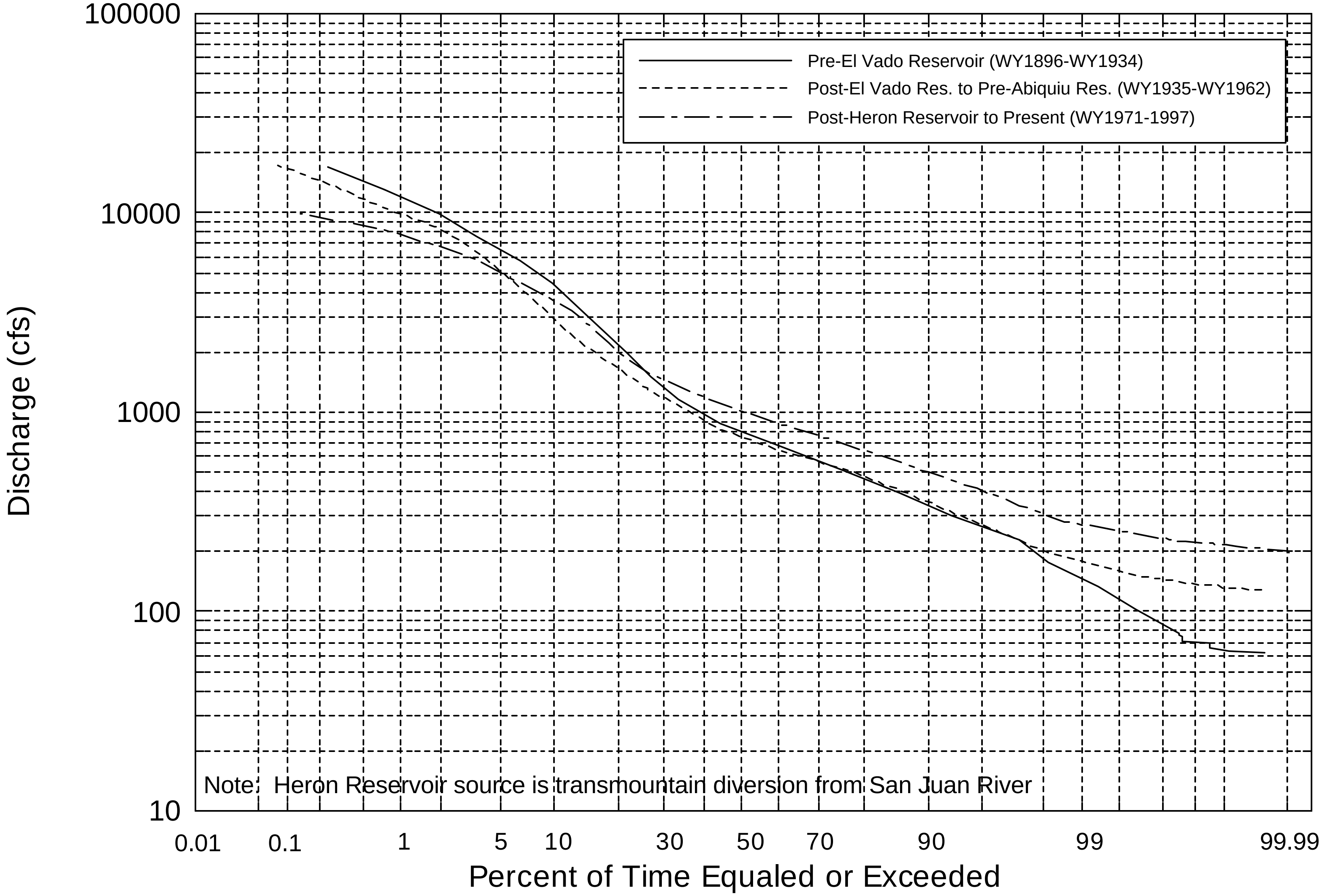


Figure 3.22. Flow-duration curves for the Otowi gage based on mean daily flow data for four different time periods.

Flow-duration curves for pre- Heron Reservoir (1971) and post-Cochiti Reservoir (1974) periods were developed for the Cochiti, San Felipe, Albuquerque, Rio Grande Floodway near Bernardo, Rio Grande Floodway at San Acacia, and San Marcial gages (**Figures 3.23 through 3.28**). At the Bernardo, San Acacia, and San Marcial gages, the post-Cochiti period was further subdivided into the following periods: 1974-1985 and 1986-1999 to reflect the cessation of diversions to the LFCC in 1985. At the San Acacia gage (Figure 3.27), a further flow-duration curve was developed that combined the Floodway gage with the diversions to the LFCC between 1974 and 1985. To represent a wide range of mean daily flows the pre- Heron and post-Cochiti, 1-percent, 50-percent and 90-percent exceedence values for each of the time periods were compared at each of the gages (**Table 3.2**). At the 1-percent exceedence level, the flows have been somewhat reduced, or have remained the same from Otowi to Albuquerque (Reaches 1, 2, and 3), in the two periods. However, downstream of Albuquerque (Reaches 4a, 4b, 5, 6, 7 and 8) the 1-percent exceedence values have increased over time. At the 50-percent exceedence level, the flows in the river have increased between Otowi and Albuquerque by 200 to 300 cfs. The major changes, however have occurred downstream of Albuquerque. At Bernardo, the median flow increased from 0 to about 550 cfs between 1974 and 1985 as a result of cessation of diversions to the Rio Grande Conveyance Channel in 1974 (Figure 3.26). Between 1986 and 1999, the reasons for the increased flows in the latter time period are not known specifically, but they probably include some San Juan Chama water, the City of Albuquerque wastewater discharge (about 69,000 ac-ft annually), controlled releases from Cochiti and other reservoirs, increases in return flows to the river, and possibly seepage from Cochiti Reservoir. At San Acacia, the same general pattern is present with increased flows in the 1974-1985 period, but the increase in the median discharge in the 1986-1999 period is due to cessation of diversions to the LFCC, and it presumably includes some of the additional flows observed at the Bernardo gage in the same time period (Figure 3.27). The same trends are also seen for the same time periods at the San Marcial gage (Figure 3.28), and it is assumed that the same explanations pertain. At the 90 percent exceedence level, the flow-duration curves show that there have been significant increases at Bernardo, San Acacia, and San Marcial.

The flow-duration data provide potential insights to reported channel adjustments, especially downstream of the gravel-bed reaches (Reaches 1 and 2). Where the bed is composed of sand (Reaches 3, 4a, 4b, 5, 6, 7 and 8), the additional flows may well be responsible for the reported degradation of the bed in Reaches 4b, 5 and 6. At the range of flows represented by the present day (1986-1999) 50-percent exceedence level there tends to be incision into a sand-bed channel that concentrates the flow and optimizes the sediment transporting capacity of the flows (Anthony and Harvey, 1991). Bed configuration in sand-bed streams is one of the most adjustable components of channel morphology, which regulates the short-term interaction of hydraulic variables, and thereby promotes a form of local equilibrium between sediment availability and transport capacity (Knighton, 1984). Given the scale of the reported incision, especially in the Rio Puerco to San Acacia reach (about 3 feet) where there is evidence of significant sediment availability in the channel (numerous braid bars), it is highly likely that the incision represents channel adjustments to the increased flows.

The flow-duration curves indicate that at Bernardo, the river has gone from being dry about 70 percent of the time in the pre-1973 period to about 1 percent of the time in the 1986-1999 period. At San Acacia, the river was dry about 10 percent of the time in the earlier period, but in the latter period it is dry less than 1 percent of the time. At San Marcial, the percentage of time that the river is dry has reduced from about 40 percent to 10 percent. Historical data compiled by Scurlock (1998) indicate that reaches of the Rio Grande probably dried up for periods of time during very dry periods (**Table 3.3**). However, given the longevity and intensity of historic use of

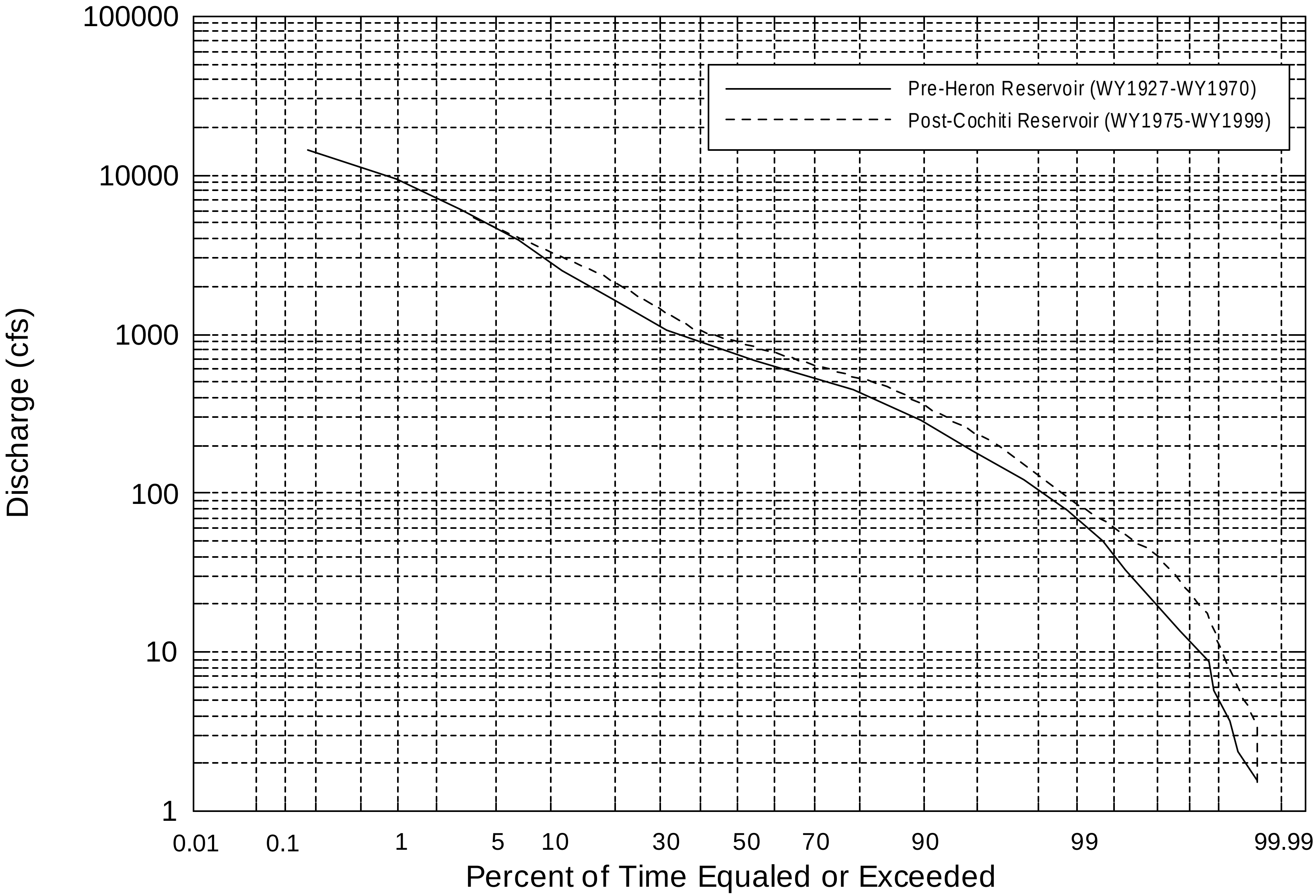


Figure 3.23. Flow-duration curves for the Cochiti gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

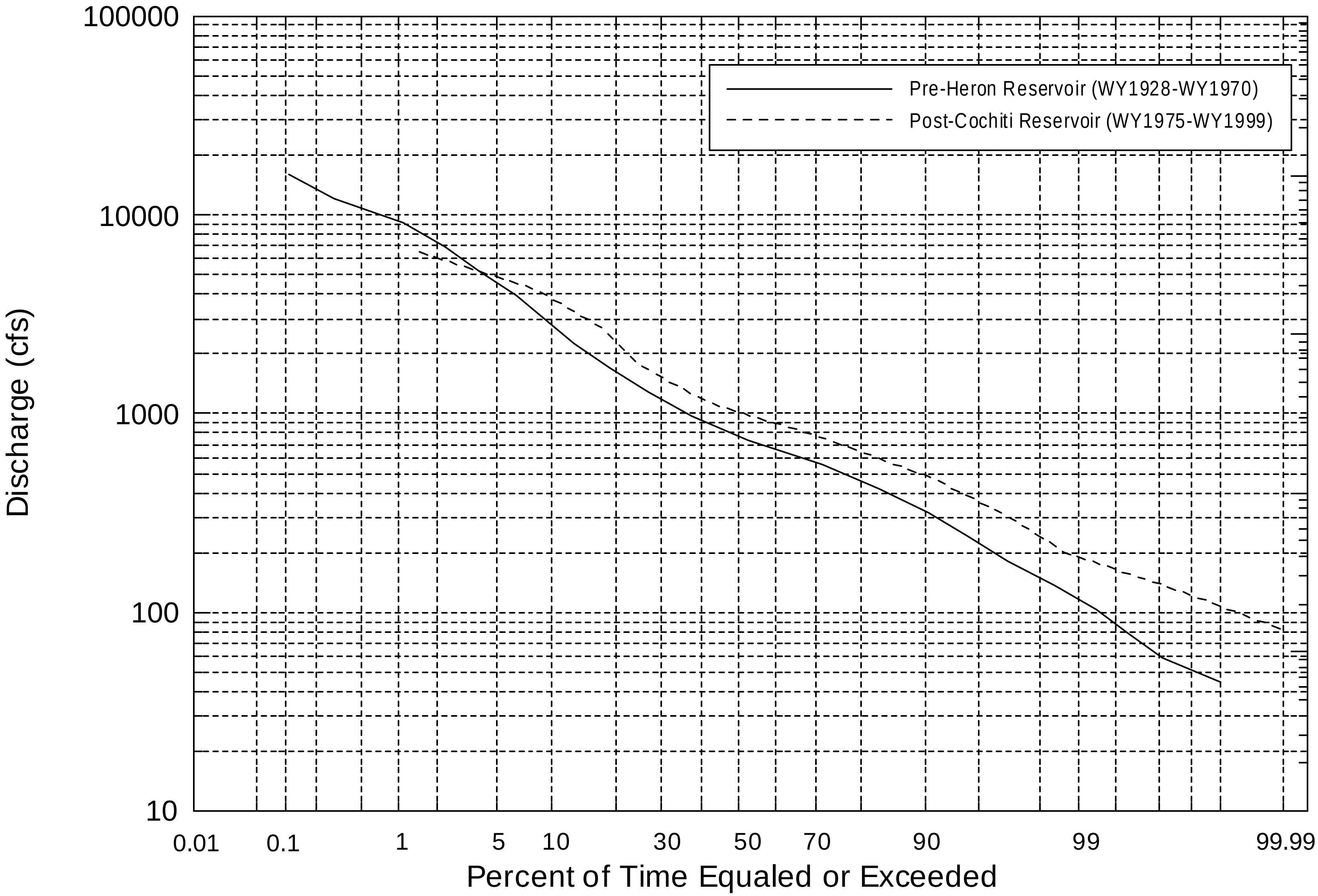


Figure 3.24. Flow-duration curves for the San Felipe gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

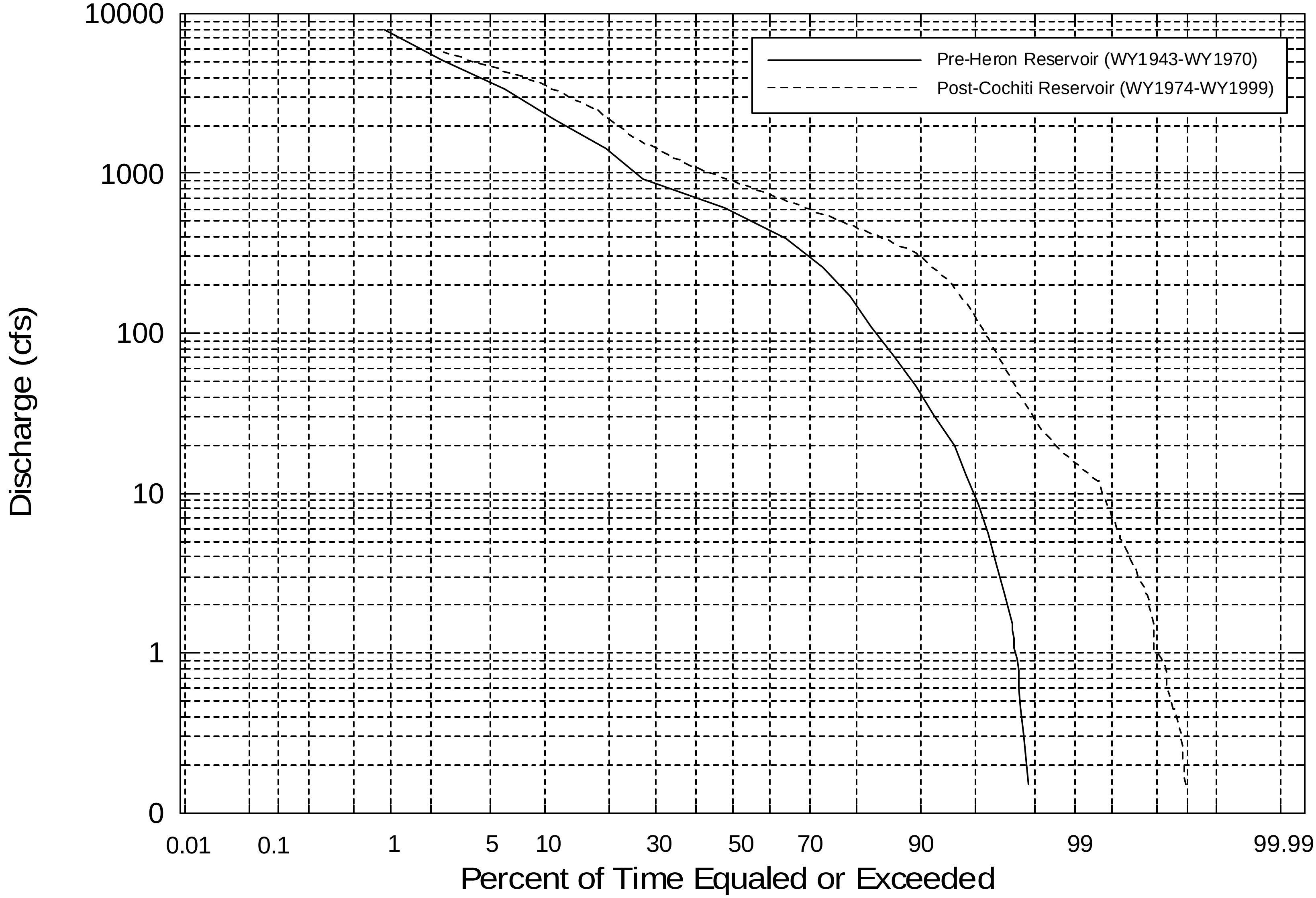


Figure 3.25. Flow-duration curves for the Albuquerque gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

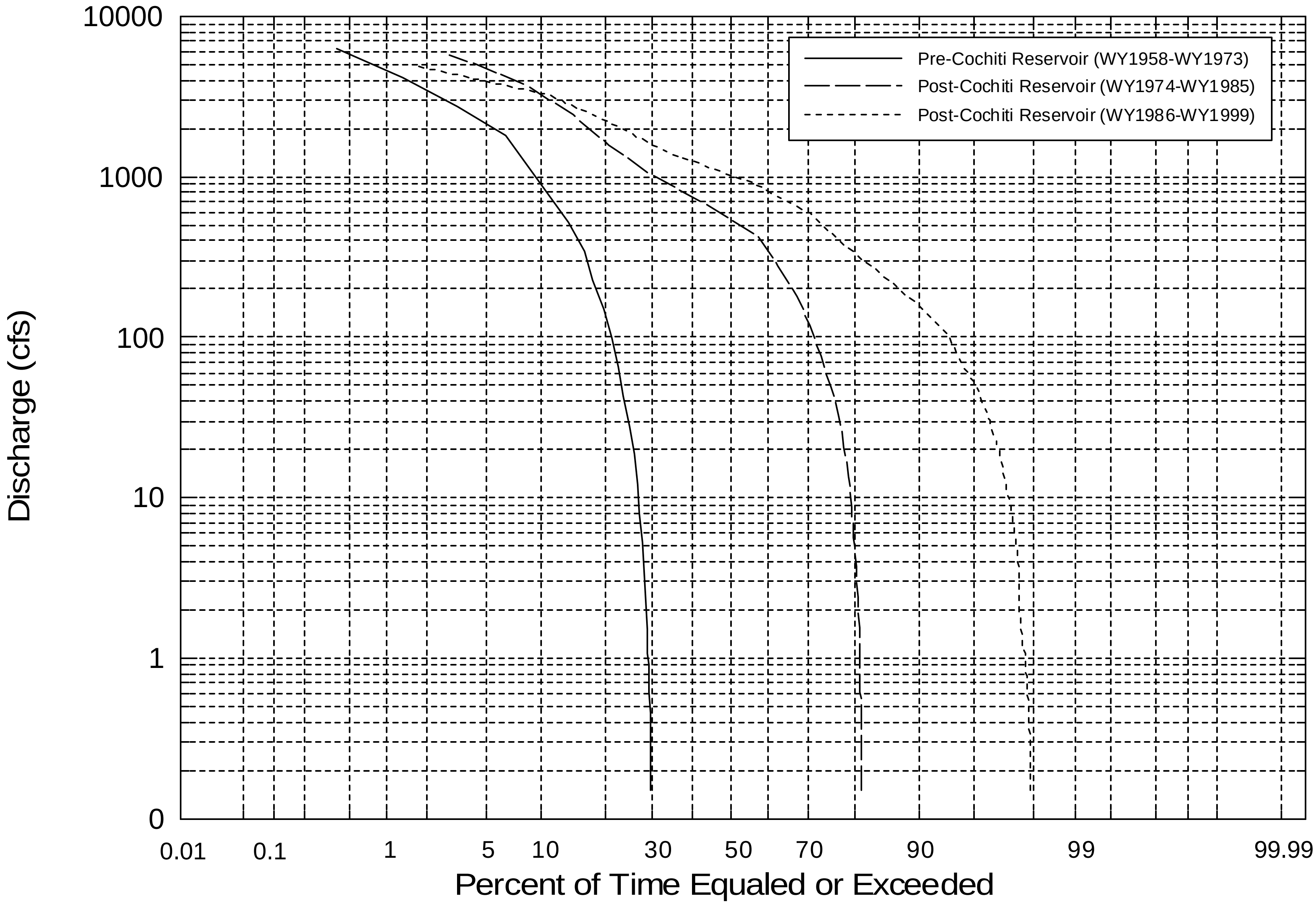


Figure 3.26. Flow-duration curves for the Rio Grande Floodway near Bernardo gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

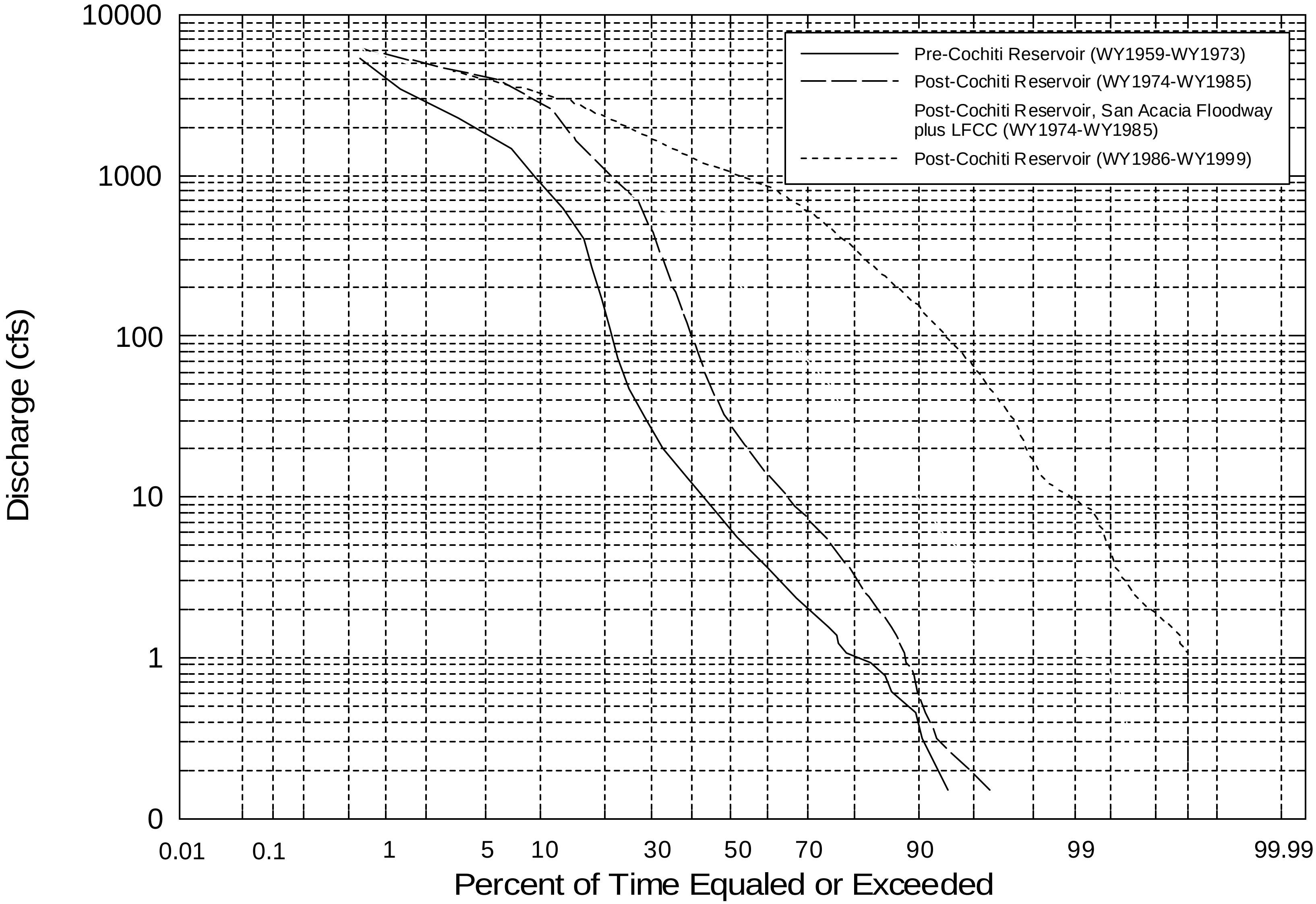


Figure 3.27. Flow-duration curves for the Rio Grande Floodway at San Acacia gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

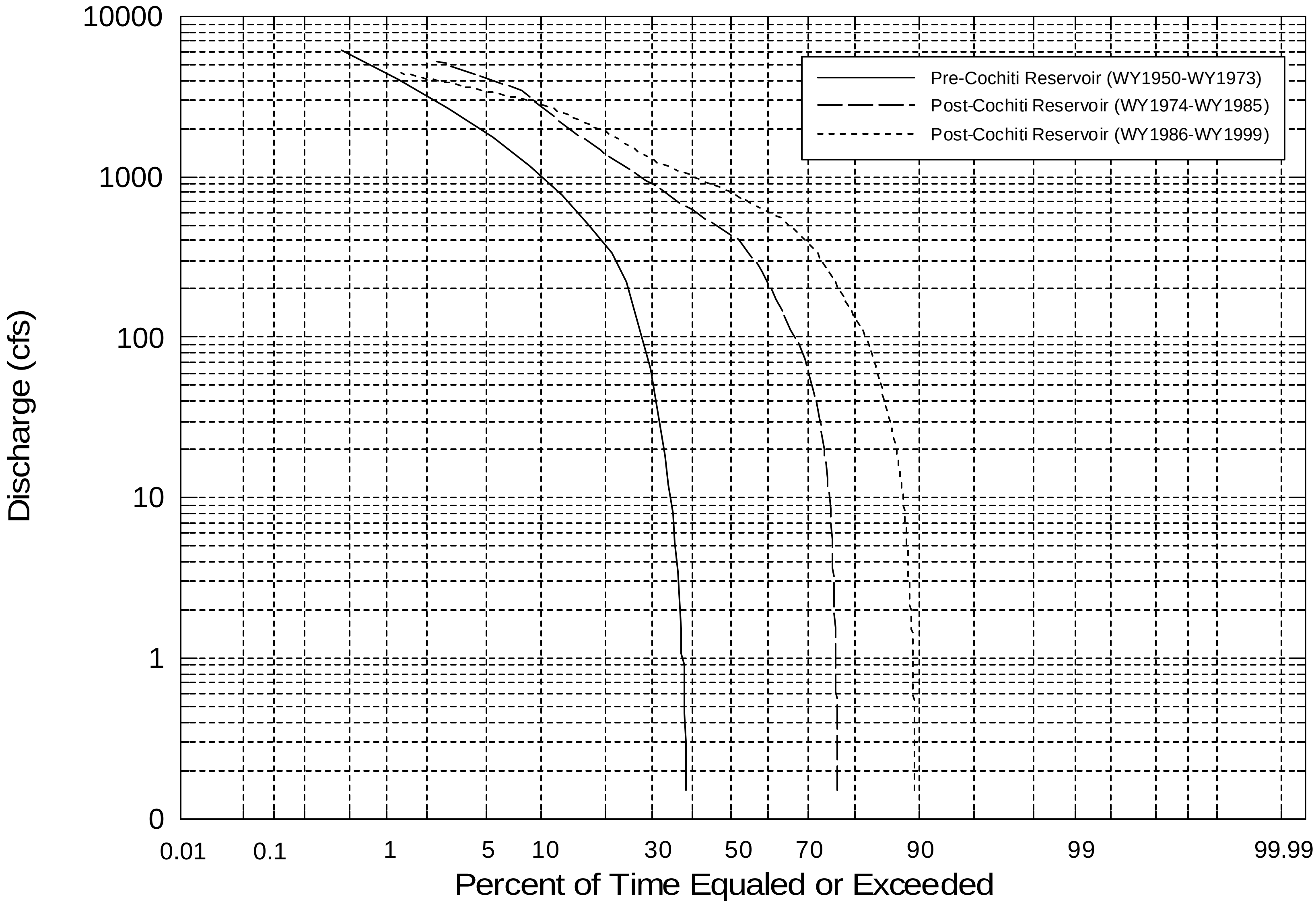


Figure 3.28. Flow-duration curves for the San Marcial gage based on mean daily flow data for pre-Heron Reservoir and post-Cochiti Reservoir periods.

Table 3.2. Summary of flow-duration statistics based on mean daily flows for the Rio Grande gages for pre-Heron Reservoir and post-Cochiti Reservoir periods.

Gage	Discharge (cfs)								
	1 Percent Exceedence			50 Percent Exceedence			90 Percent Exceedence		
	Pre-1970*	Post-1973**	1986-1999	Pre-1970*	Post-1973**	1986-1999	Pre-1970*	Post-1973**	1986-1999
Otowi	12,000[1]	8,000[2]	---	700	1,000	---	300	500	---
Cochiti	9,000	9,000	---	750	940	---	200	400	---
San Felipe	9,500	7,000	---	780	1,000	---	320	490	---
Albuquerque	7,500	7,500	---	580	900	---	40	300	---
Bernardo Floodway	4,700	---	---	0	550***	1,000	0	0***	150
San Acacia Floodway	4,000	5,800***	5,800	8	30***	1,000	3.5	5.5***	150
San Marcial	4,200	5,200	---	0	450***	800	0	0***	0

[1]Pre-El Vado Reservoir (1896-1934)
[2]Post-Heron (1971-1997)
*Pre-1970: Start of filling of Heron Reservoir
**Post-1973: Start of filling Cochiti Reservoir
***1974-1985: Cessation of diversion to the Rio Grande Flow Conveyance Channel

Table 3.3. Years when Rio Grande was dry (Surlock, 1998).	
Year	Location
1752	Dry for almost 400 miles (border to border)
1855	Dry 25 miles above Las Cruces
1861	Dry from Socorro to below El Paso
1879	Dry below Isleta
	Dry below San Felipe for 1 to 2 months
1888	Dry at Socorro (upstream use)
1889	Dry below Isleta in summer
1892	Dry at Los Lunas
1895-1907	Middle Rio Grande dry during irrigation seasons
1896	Dry at San Marcial
1817-1907	Dry at San Marcial every irrigation season
1903	Dry at March (Isleta-Tome)—ran at intervals and dry again
1904	Dry at San Marcial (March-July)
	Dry at San Marcial (summer)
1908	Dry below Cochiti Pueblo
1910	Dry at San Marcial (summer)
1911	Almost dry (late July-early August) in Tome area
1913	Dry at San Marcial (summer)
1917-1919	Dry at San Marcial
1921	Dry at San Marcial (150 days) – see pg. 29
1922	Dry at San Marcial (150 days) – see pg. 73

the valley for agriculture it is quite likely that reported periods of no flow were related to abstraction of flows for irrigation (Crawford et al., 1993).

3.3. Sedimentology

The available sediment data on the Middle Rio Grande include (1) bed-sediment gradation data from USBR range lines that were collected over various periods of time, (2) bed sediment gradation data from the USGS gages at Albuquerque, Bernardo and San Acacia that were collected over varying periods of time, (3) suspended-sediment samples collected by the USGS at the Cochiti, San Felipe, Bernalillo, Albuquerque, Bernardo, San Acacia, San Marcial gages on the Rio Grande, (4) suspended-sediment data collected on Galisteo Creek, Jemez River, Rio Puerco and Rio Salado, and (5) bed-material load data collected by the USGS at the Cochiti, San Felipe, Bernalillo, Albuquerque, Bernardo, San Acacia and San Marcial gages for various periods of time. Additionally, MEI collected 20 samples of bed material for this project. From the sediment data, it is possible to evaluate spatial differences in the caliber of the bed material through the reach, and to evaluate temporal changes at various locations for the periods of record, that in general pre-and post-date the construction of Cochiti Dam. Development of rating curves for both suspended sediment (suspended bed-material load) and the bed load at the various gages for different periods, and integration of the rating curves with the flow volumes provide estimates of total sediment load, and permit evaluation of changes through time and space.

3.3.1. Bed-Material Gradations

Sampling of bed material over time was conducted at various range lines through the Middle Rio Grande by the USBR and contractors for the USBR (FLO Engineering, and TetraTech, Inc.). **Figures 3.29 through 3.35** present the gradation parameters (D_{16}, D_{50}, D_{84}) for the sediment samples collected between 1970 and 1998 for six range lines located between Cochiti Dam and about Bernalillo. In all of the plots, the data collected between 1970 and 1980 represent a single sample collected at an unpublished location on the range line. The data collected after 1992 represent the average gradations of at least 3 samples collected across the individual range lines (**Figure 3.36**). An average value was computed for each range line for the latter data set, and this value was used in Figures 3.29 through 3.35, but as can be seen on Figure 3.36, the D_{50} can vary by as much as two orders of magnitude across the range line. The data show that following closure of Cochiti Dam in 1973, the bed-material gradations have coarsened, which is the expected response downstream of a dam that has a very high trap efficiency (Williams and Wolman, 1984).

However, the earlier bed-material data may well be biased by the single sample that was taken at each range line, and the observed changes through time may not be as dramatic as they appear to be, at least upstream of Angostura Diversion. Prior to closure of Cochiti Dam it is doubtful that the bed material between Cochiti Dam was sand-sized. Culbertson and Dawdy (1964) reported that the bed was A-- *a gravel alluvium over which a veneer of sand is transported. At higher discharges and correspondingly large sediment transport, the bed generally has areas bare of sand, with gravel exposed to the flow. At times an entire cross section may have a gravel bed* A. Rittenhouse (1944) stated A*in the upper part of the Middle 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 percent in the upper 5 feet of the deposits* A. Nordin and Beverage (1965) reported that A*between Cochiti and San Felipe, the channel is braided between many bars and islands composed of coarse gravel and cobbles. As at Otowi, the bed is composed of sand at bw discharges and of sand and gravel at higher flows. Downstream of the Jemez River, the Rio Grande is a sand bed stream* A. These quotations tend to be supported by present day observations of the gravel and cobble bed materials in the Rio Grande in the vicinity of the Santa Clara Pueblo, which is located above Cochiti Reservoir and downstream of the Rio Chama confluence, and is, therefore, representative of the pre-Cochiti bed conditions downstream of the dam. The sand-and-gravel composition of the floodplain sediments that are exposed in the banks of the river downstream of Cochiti Dam is also indicative of the range of sediments that were being transported by the river, and hence the likely bed-material gradations. The relatively small amount of channel bed degradation that has occurred in the reach immediately downstream of Cochiti Dam tends to further support the coarse nature of the bed materials prior to closure of the dam (Richard, 2001).

Bed-material data collected by the USGS at the Albuquerque, Bernardo and San Acacia gages are presented in **Figures 3.37 through 3.39,** respectively. At the Albuquerque gage (Figure 3.37) there has been a slight coarsening of the bed material since the late 1960s, but the D_{50} of the bed material is still sand-size (<2mm). The D_{84} values are remarkably similar through time, and reflect the presence of some gravel in the bed of the river (Rittenhouse, 1944), and are not indicative of a general bed-coarsening trend. The slight coarsening of the D_{50} values probably is due to some channel incision at the Albuquerque gage since about 1974. Evaluation of the discharge rating curves for the gage show about 2 feet of downward shift between 1974 and 2001 at flows less than about 4,000 cfs (**Figure 3.40**). At the Bernardo gage (Figure 3.38) the data show that there may have been a very minor increase in the bed-material size between 1968 and 1990, but even the D_{84} values are still very much within the range of sand sizes. A

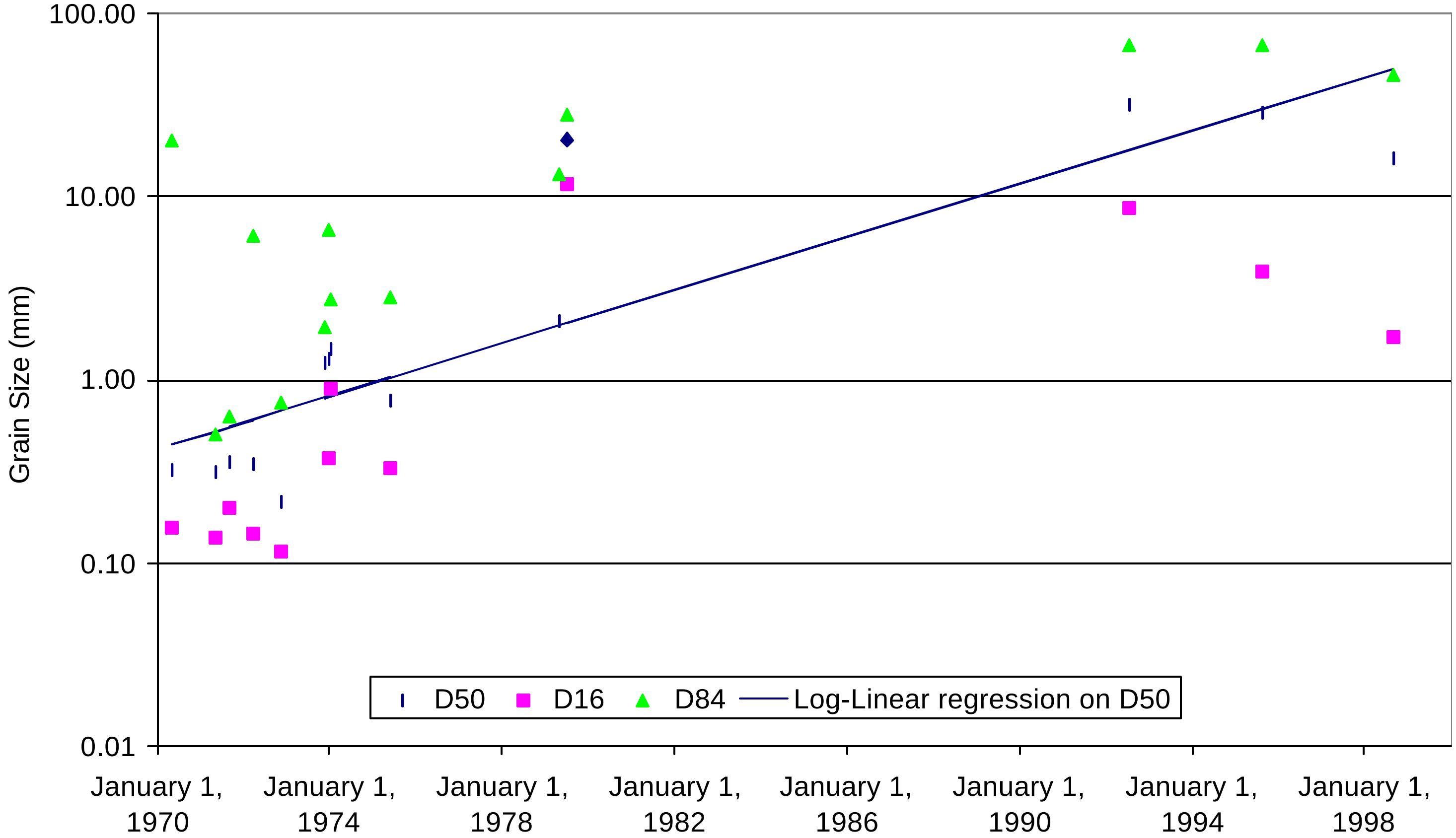


Figure 3.29. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-3, located 3.3 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

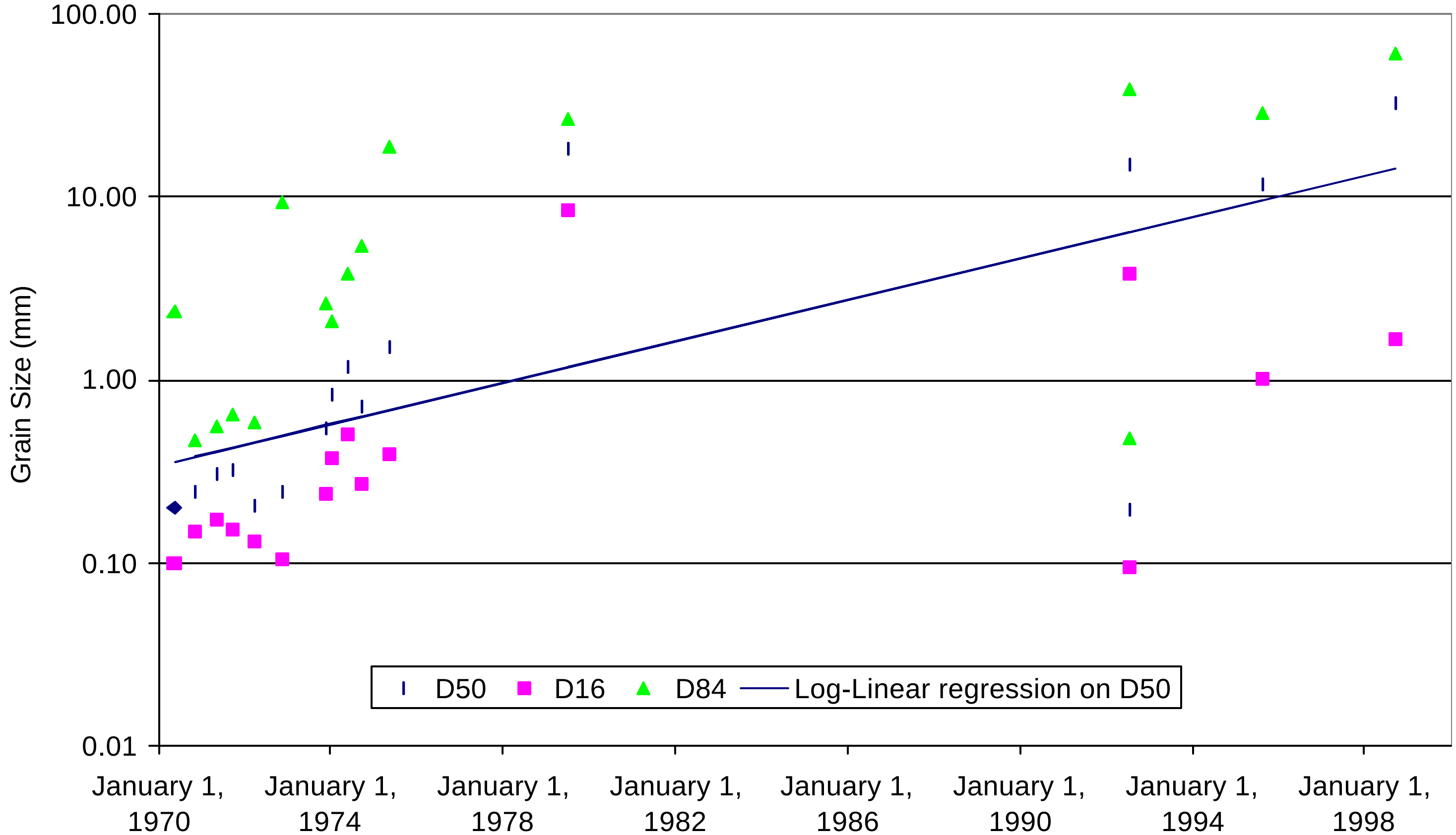


Figure 3.30. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-5, located 5.1 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

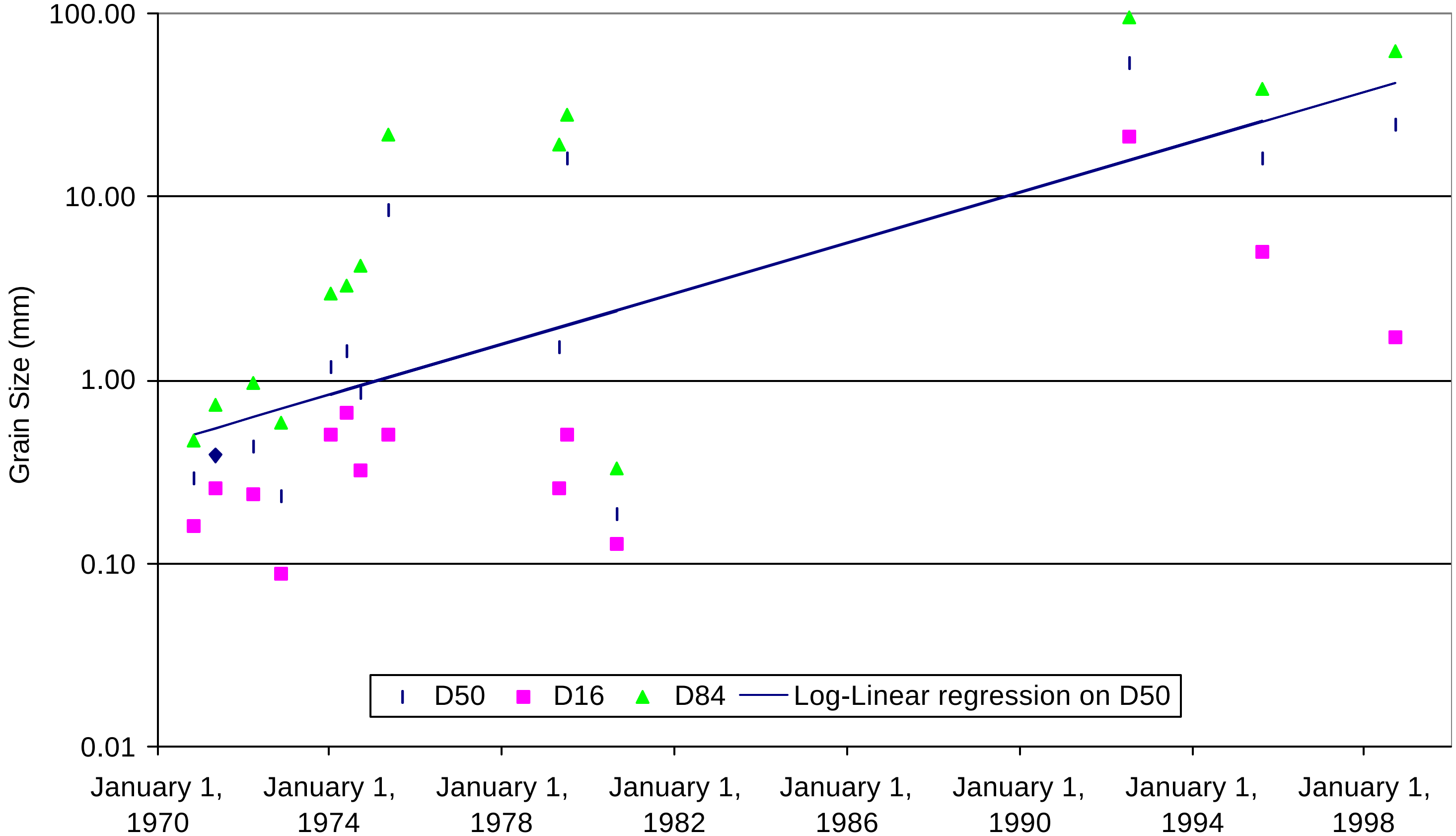


Figure 3.31. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-8, located 7.6 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

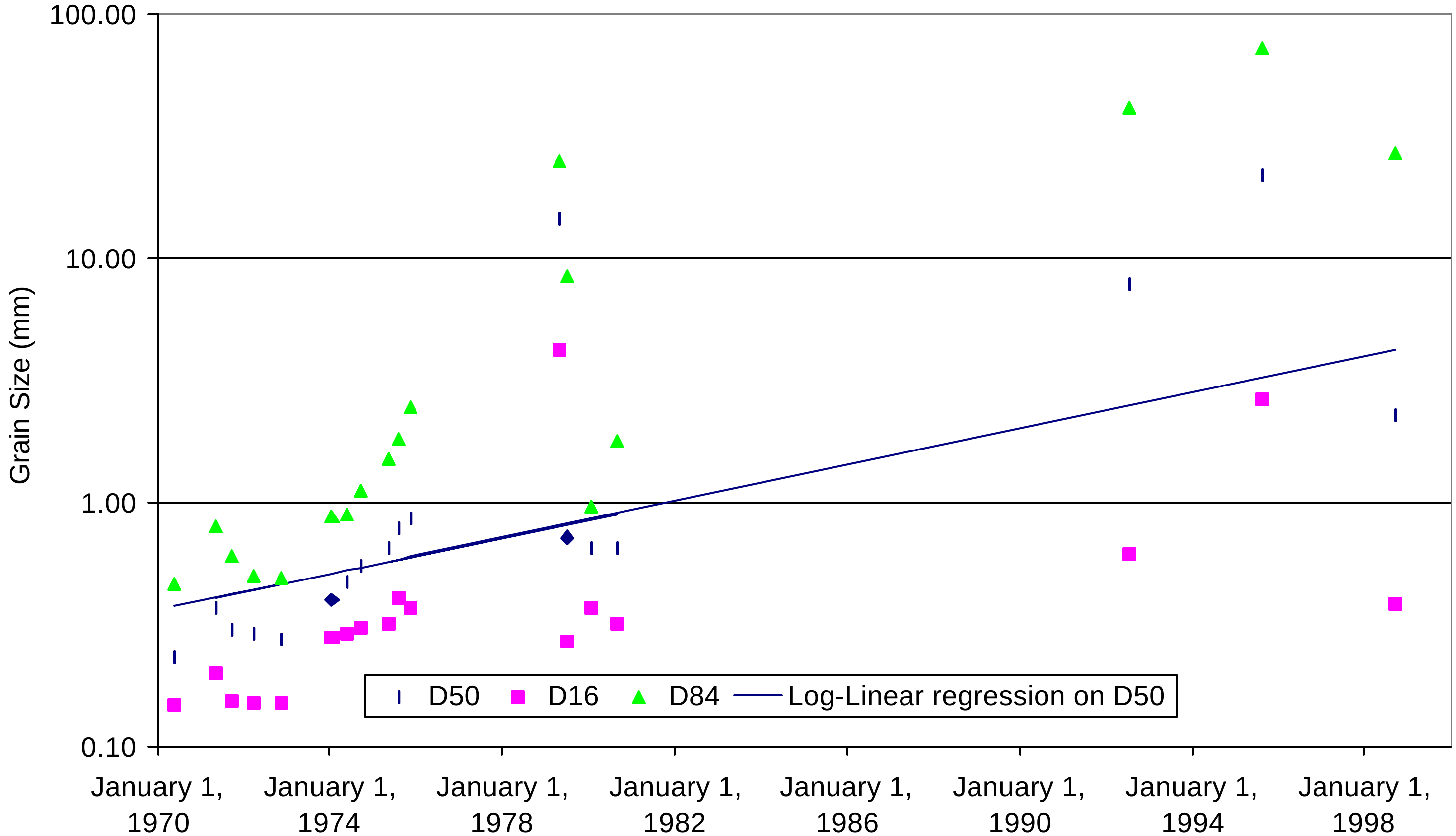


Figure 3.32. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-16, located 14.9 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

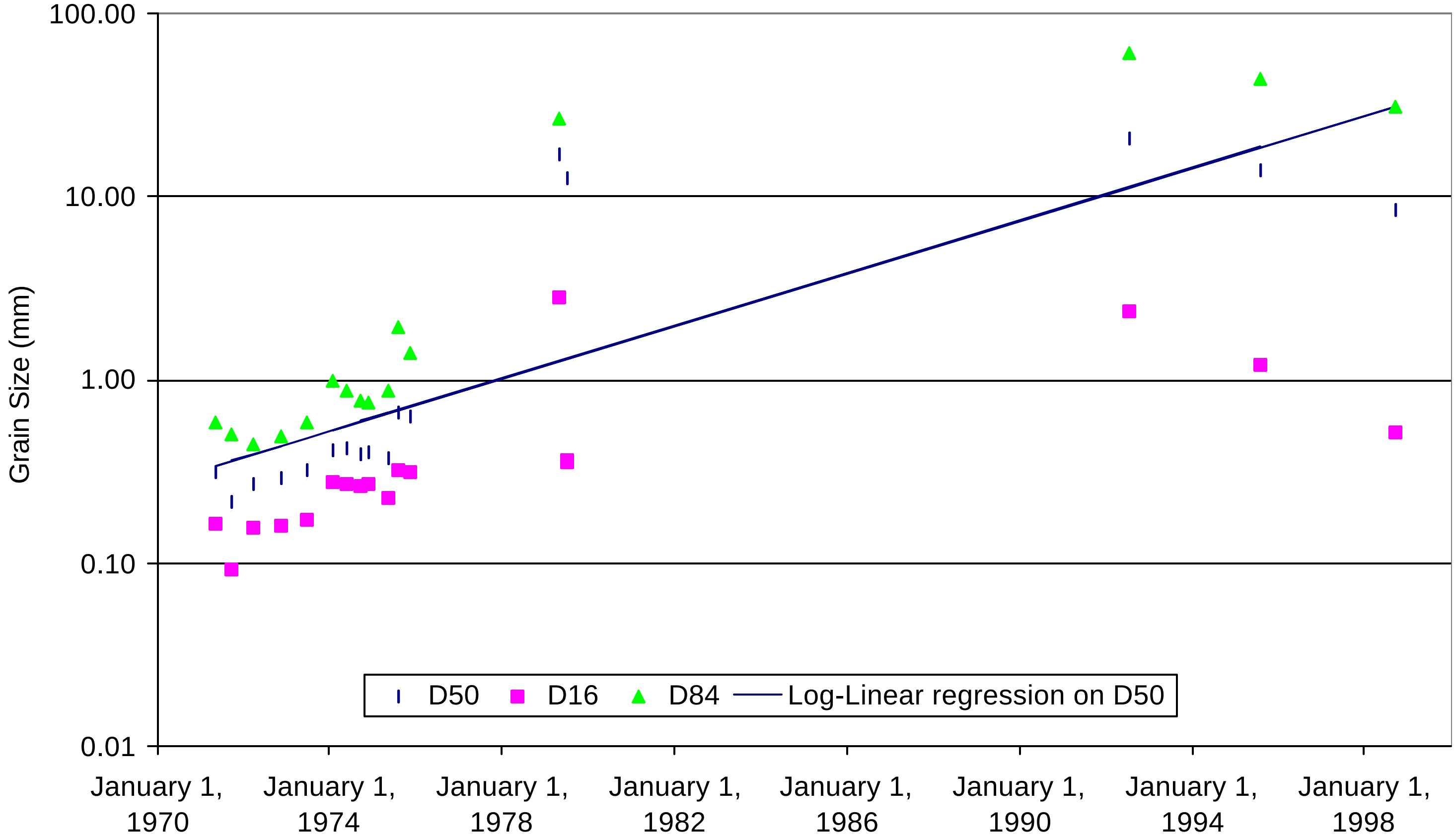


Figure 3.33. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-20, located 18.7 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

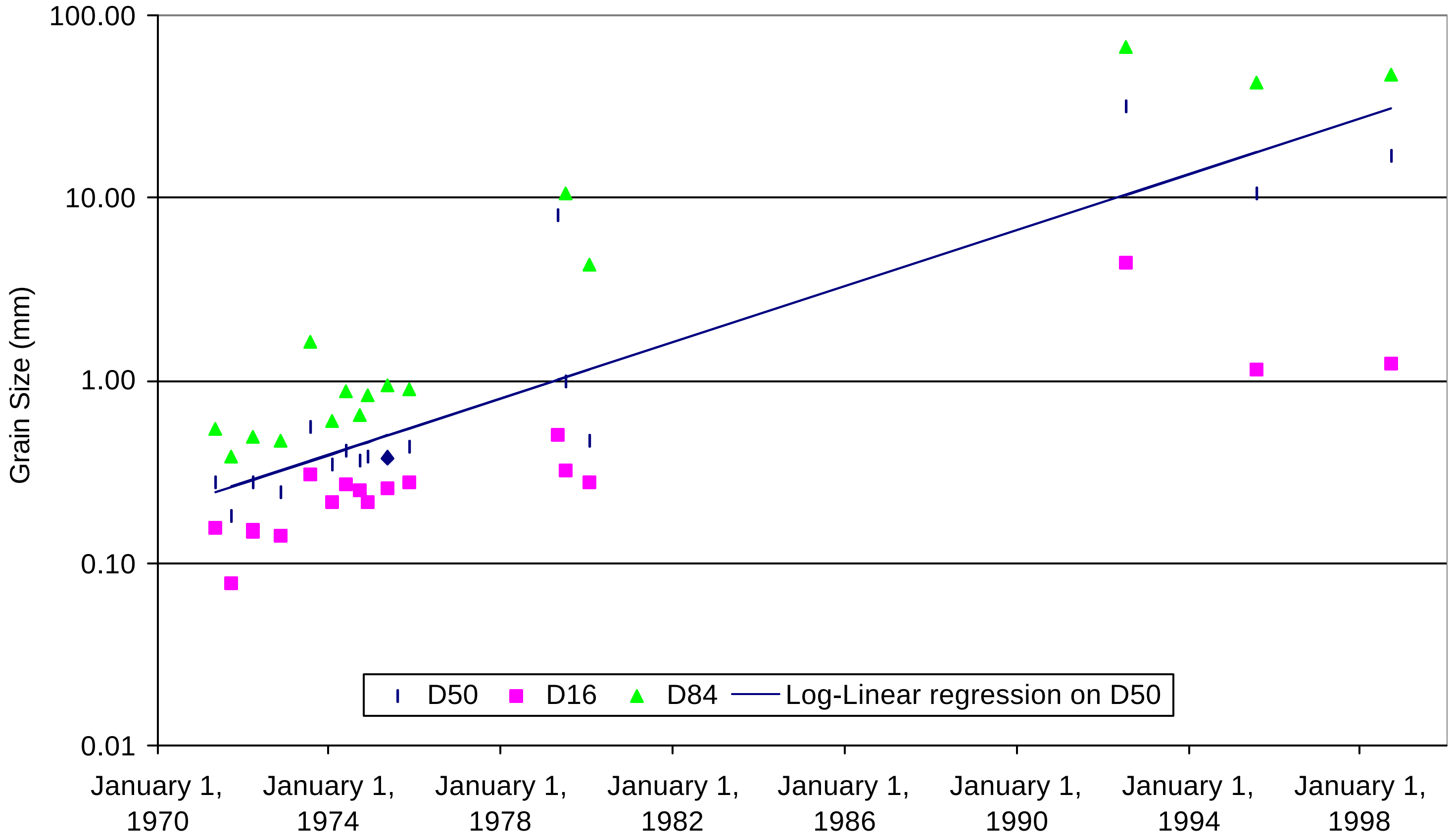


Figure 3.34. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-22, located 20 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

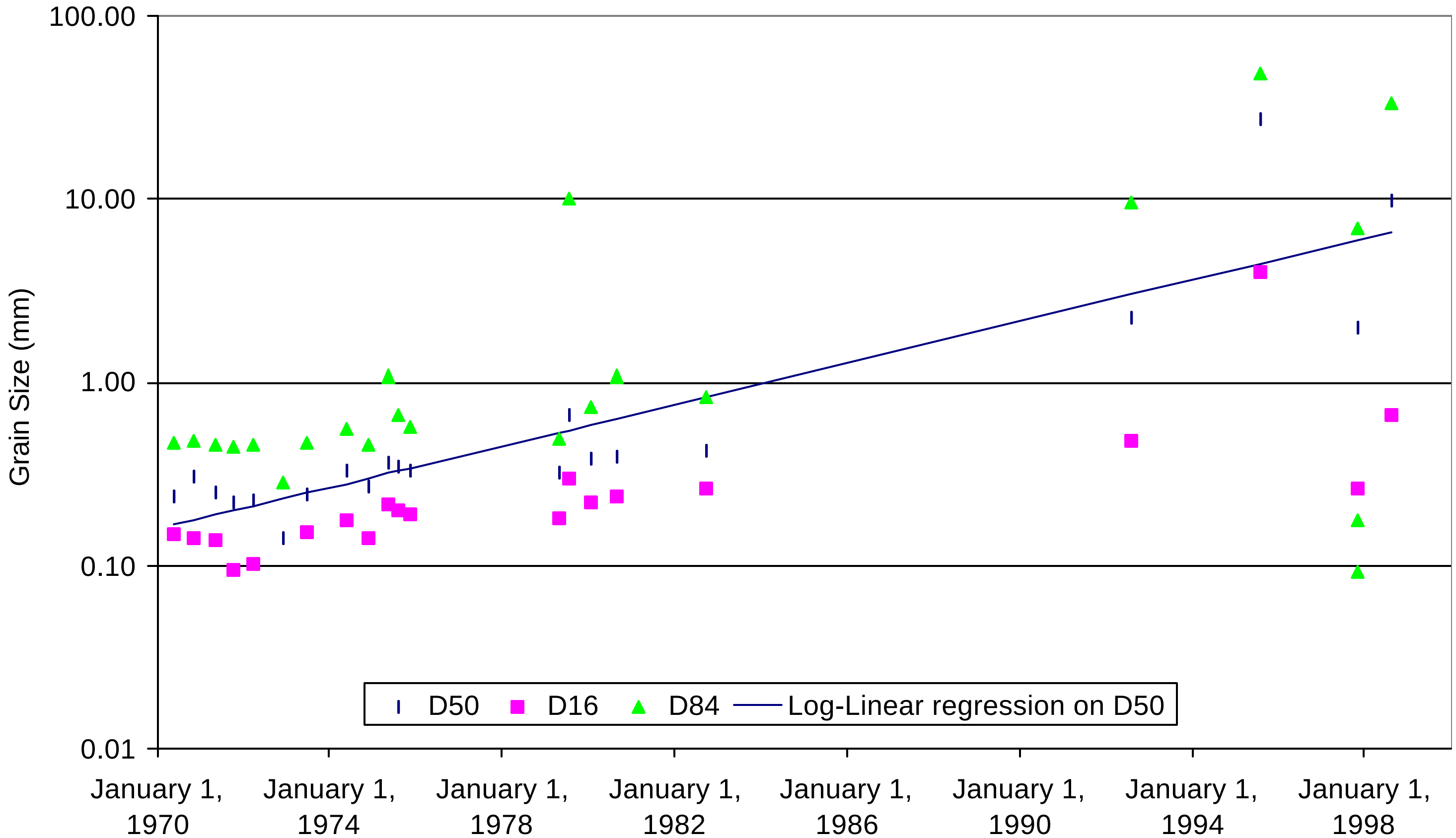


Figure 3.35. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-28, located 25.6 miles downstream of Cochiti Dam. The best-fit regression line for the D_{50} values is also shown.

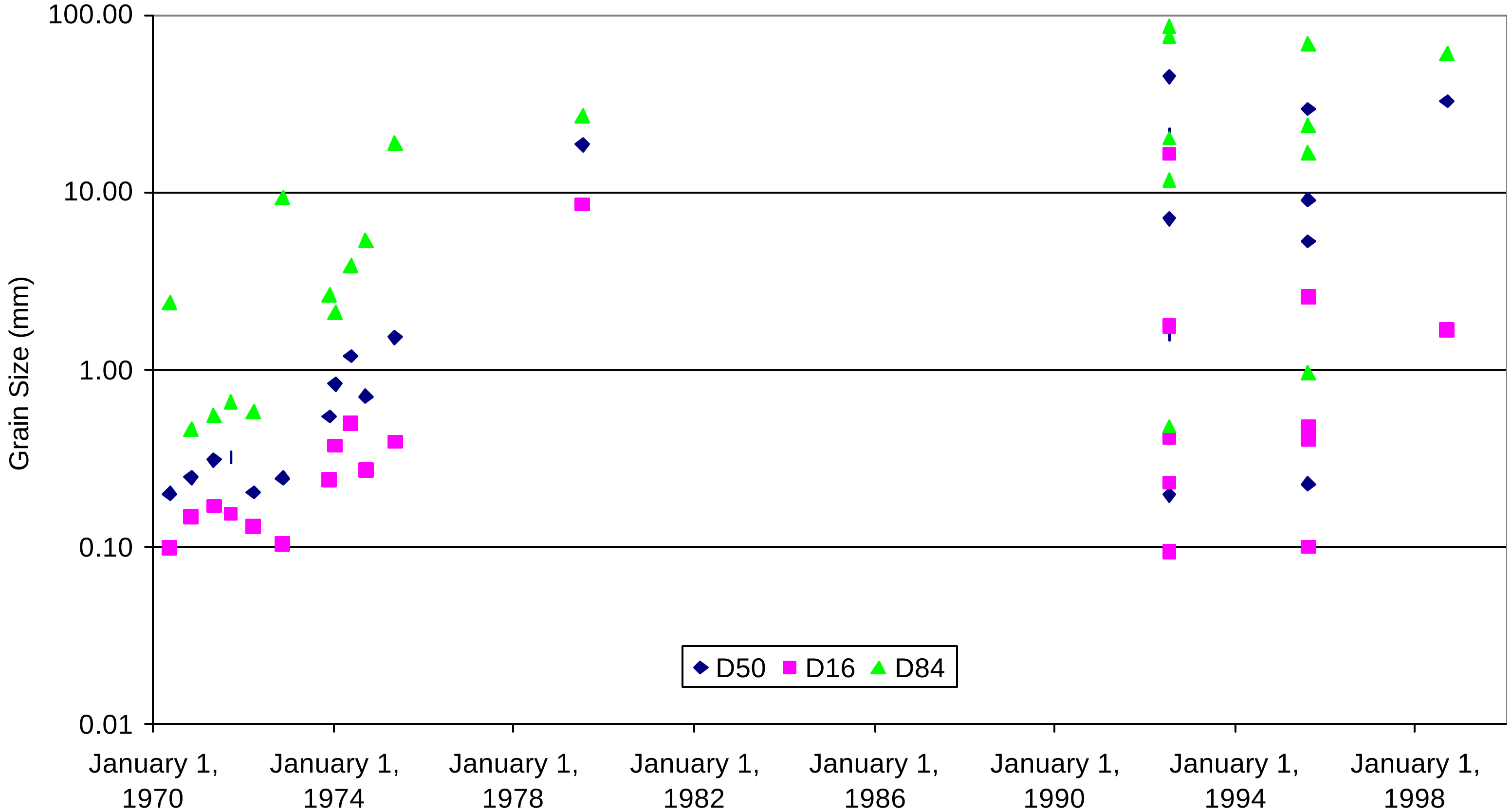


Figure 3.36. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at Range CO-5, located 5.1 miles downstream of Cochiti Dam. Note the number of samples collected across the range lines in the latter period of time and the range of sizes encompassed by the individual samples.

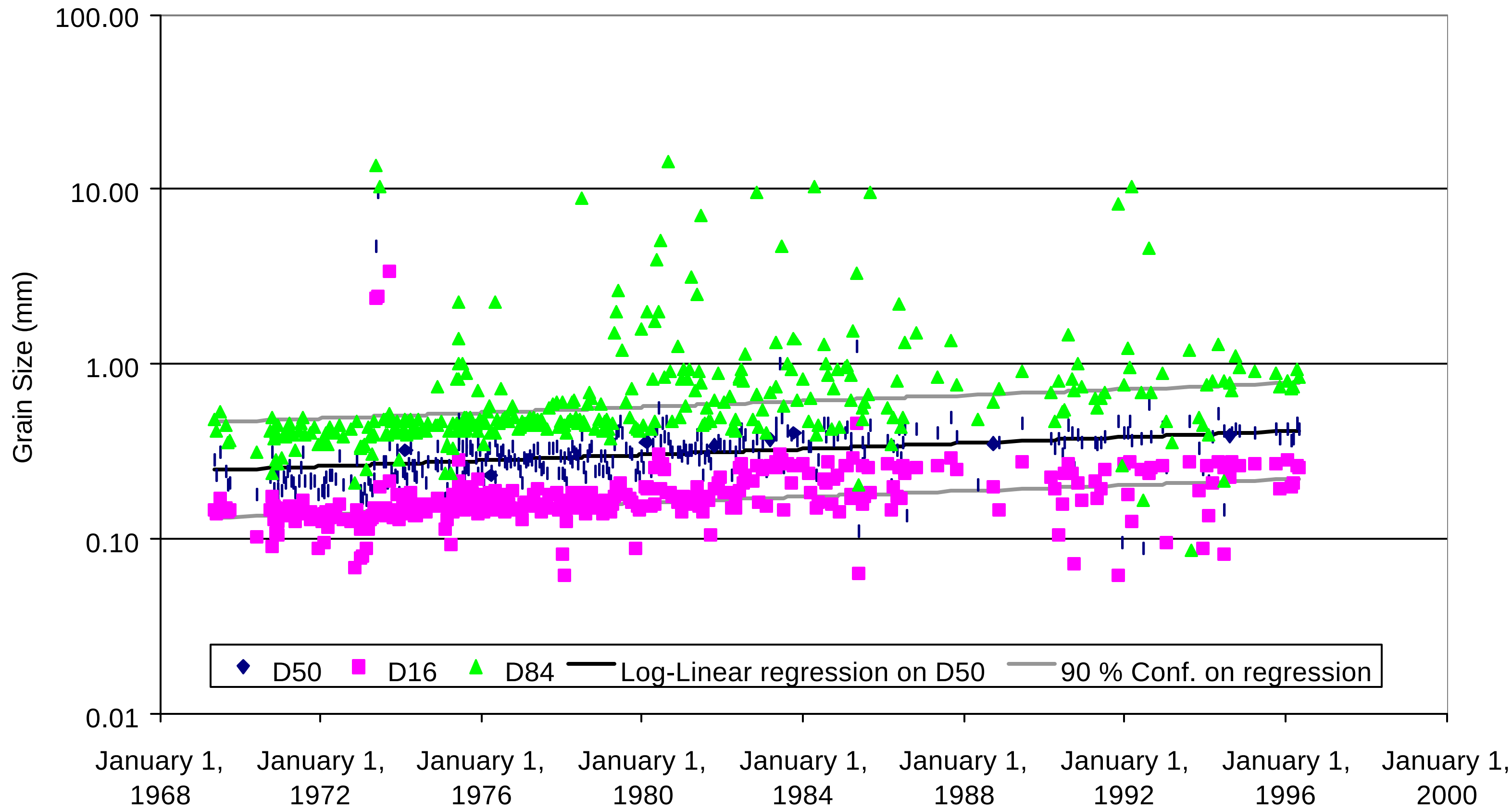


Figure 3.37. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at the Albuquerque gage. Ninety percent confidence bands on the D_{50} regression are also shown.

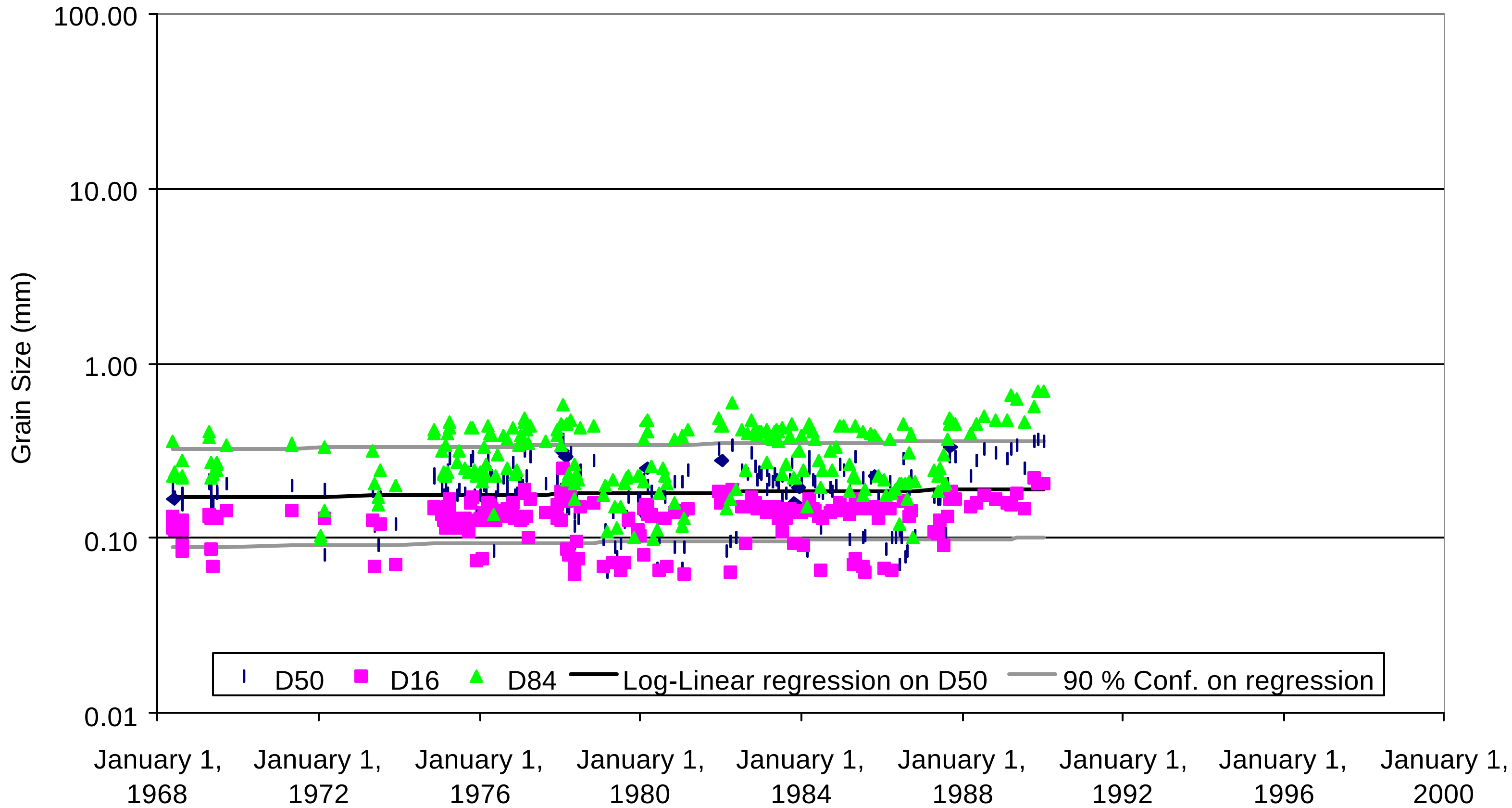


Figure 3.38. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at the Bernardo gage. Ninety percent confidence bands on the D_{50} regression are also shown.

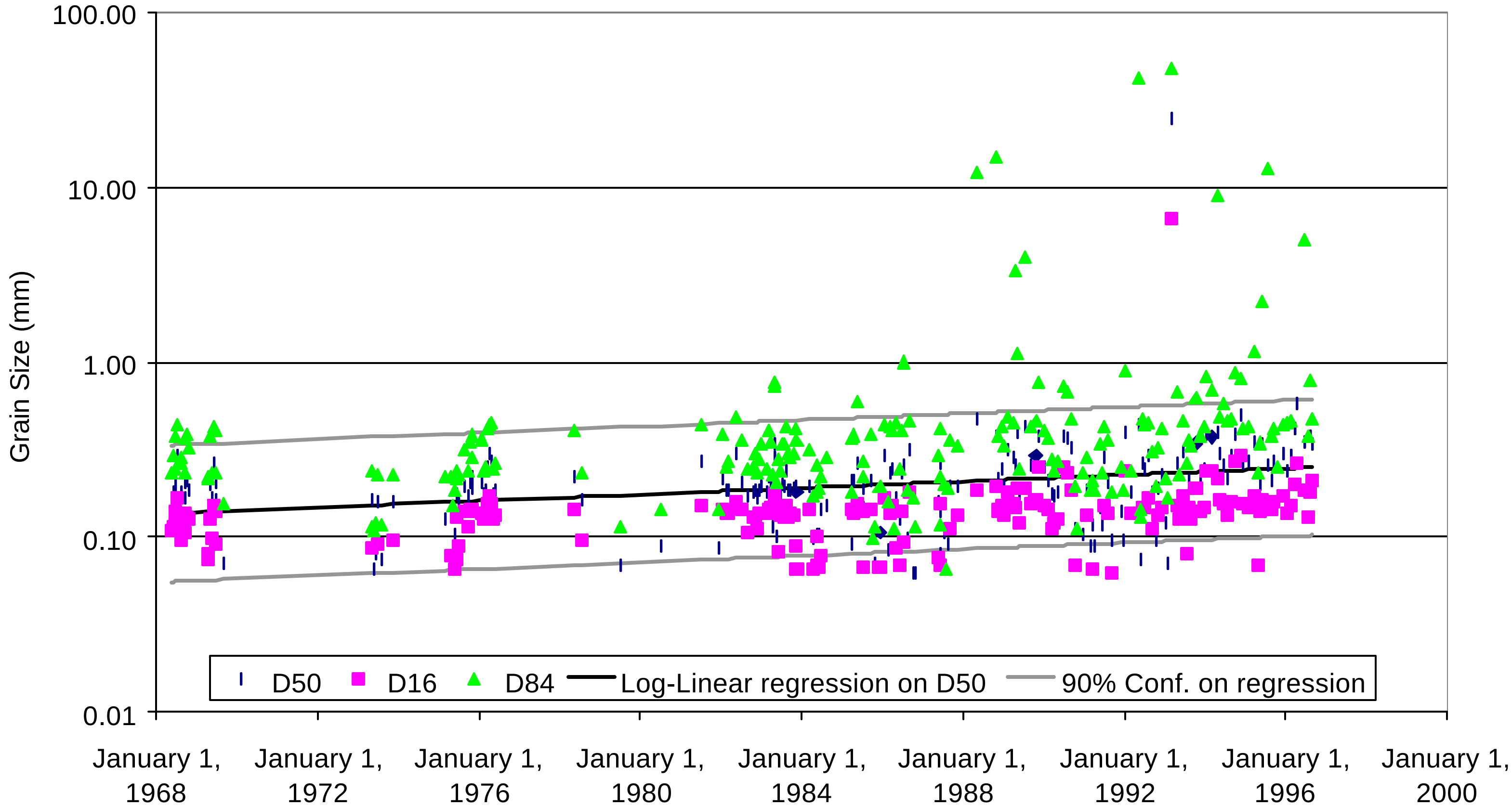


Figure 3.39. Bed-material gradation parameters (D_{16}, D_{50}, D_{84}) plotted against time at the San Acacia gage. Ninety percent confidence bands on the D_{50} regression are also shown.

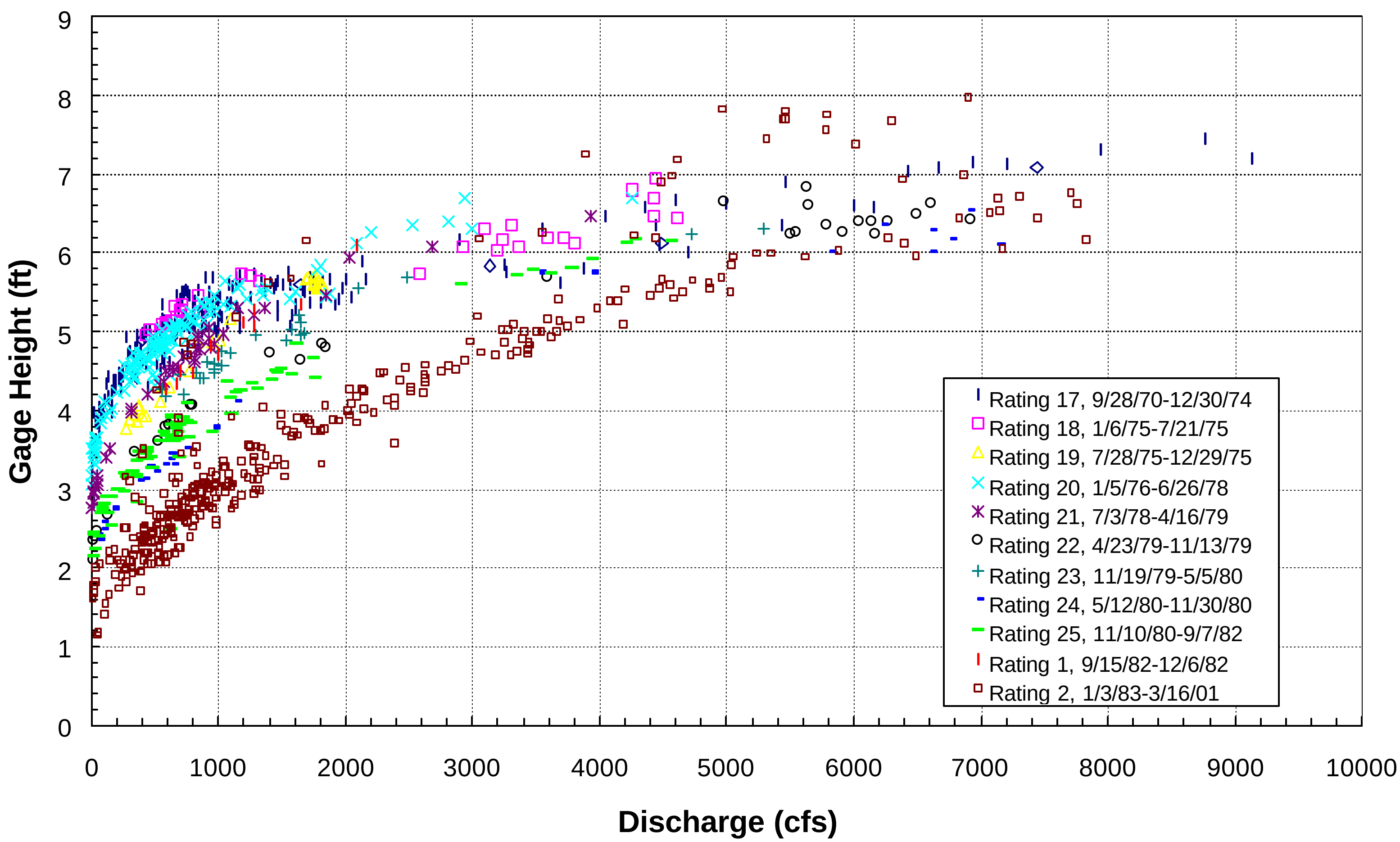


Figure 3.40. Discharge rating curves for the Albuquerque gage between 1974 and 2001, showing the downward shift of the rating through time.

general coarsening trend is apparent at the San Acacia gage (Figure 3.39). The D_{50} values are still well within the sand range, but post-1984, the D_{84} values have increased, which suggests that the bed material may be coarsening. The coarsening may be related to the operation of the LFCC. Between 1958 and 1985, the bulk of the flows below San Acacia were conveyed in the LFCC, but since that time the flows have been conveyed in the river (Crawford et al., 1993).

Figure 3.41 provides a summary of the changes in the D_{50} of the bed material through both time and space. It is apparent that, between Cochiti and Bernalillo, there has been a general coarsening of the bed material and that the coarsening trend has progressed in the downstream direction through time. Because of the uncertainty associated with the samples from the USBR range lines in the early period of the record, it is not possible to unequivocally assess the absolute magnitude of the change. However, based on the reports of Rittenhouse (1944) and Culbertson and Dawdy (1964), and observations of the bed material upstream of Cochiti Dam, it is highly likely that the data in Figure 3.41 greatly exaggerate the magnitude of the change in the bed-material gradations as least as far downstream as Angostura Diversion. The significantly greater amount of channel degradation below the Angostura Diversion in the post-Cochiti period would tend to support the presence of finer bed material (Richard, 2001). Figure 3.41 also indicates that there has been a minor coarsening of the bed material at the Albuquerque and San Acacia gages, and very little, if any, change at the Bernardo gage. At these gage sites the bed material is still sand-size (<2mm). **Table 3.4** provides a summary of the changes in the D_{50} numerical values (based on the regression lines shown in Figure 3.41) through the project reach and through time. Based on the D_{50} values, it is apparent that the bed material of the Rio Grande is now primarily gravel-size (>2mm) between Cochiti Dam and Bernalillo. Downstream of Bernalillo, it is equally apparent that the bed of the river is composed of sand-size sediment (<2mm).

Baird (2001), following his analysis of the available sediment data, concluded that the Angostura to Bernalillo reach of the Rio Grande is now a gravel-bed channel where it was historically a sand-bed channel. He also concluded that the Rio Puerco to San Acacia reach has changed from a sand-bed channel to a partially gravel-bed channel, and that a similar change in the bed-material composition had occurred in the San Acacia to Escondida reach. He estimated that the bed in the San Acacia to Escondida reach will become entirely gravel within about a 3-year period. Although not implicitly stated, it appears that Baird (2001) based his conclusion regarding future bed coarsening in the San Acacia to Escondida reach on the bed lowering that occurred between 1962 and 1999 (~9.6 feet) that he assumed to be the result of upstream reservoir construction and reduced sediment delivery in the entire basin. In order to evaluate possible bed coarsening, in early September 2001, MEI collected 20 samples of the bed material in the deepest part (thalweg) of the of the Rio Grande and certain tributaries to the Rio Grande under low-flow conditions. Additionally, 2 pebble counts (Wolman, 1954) were made at coarse-grained riffles in the Rio Grande, located at the Rio Salado confluence and the confluence with the Arroyo de la Parida.

Table 3.5 summarizes the sediment gradation parameters for each of the 20 bed-material samples (S1-S20) and the 2 pebble counts (WC1, WC2). Sample 20 was collected at the USGS gage site (Albuquerque) at Central Avenue, where the bed material may have coarsened slightly since the last reported sampling in 1996. The D_{50} value has increased from about 0.45 mm (Figure 3.37) to 0.6 mm, and the D_{84} value has increased from about 0.8 mm to about 19 mm. However, the D_{84} value is very similar to others recorded at this gage between 1972 and 1992 (Figure 3.37), and may, therefore, only reflect the variation in the bed material at this location and not a coarsening trend. Sample 3 was collected at the USGS gaging station at San Acacia. Based on this sample the D_{50} has increased from about 0.5 mm (Figure 3.39) to 1.1

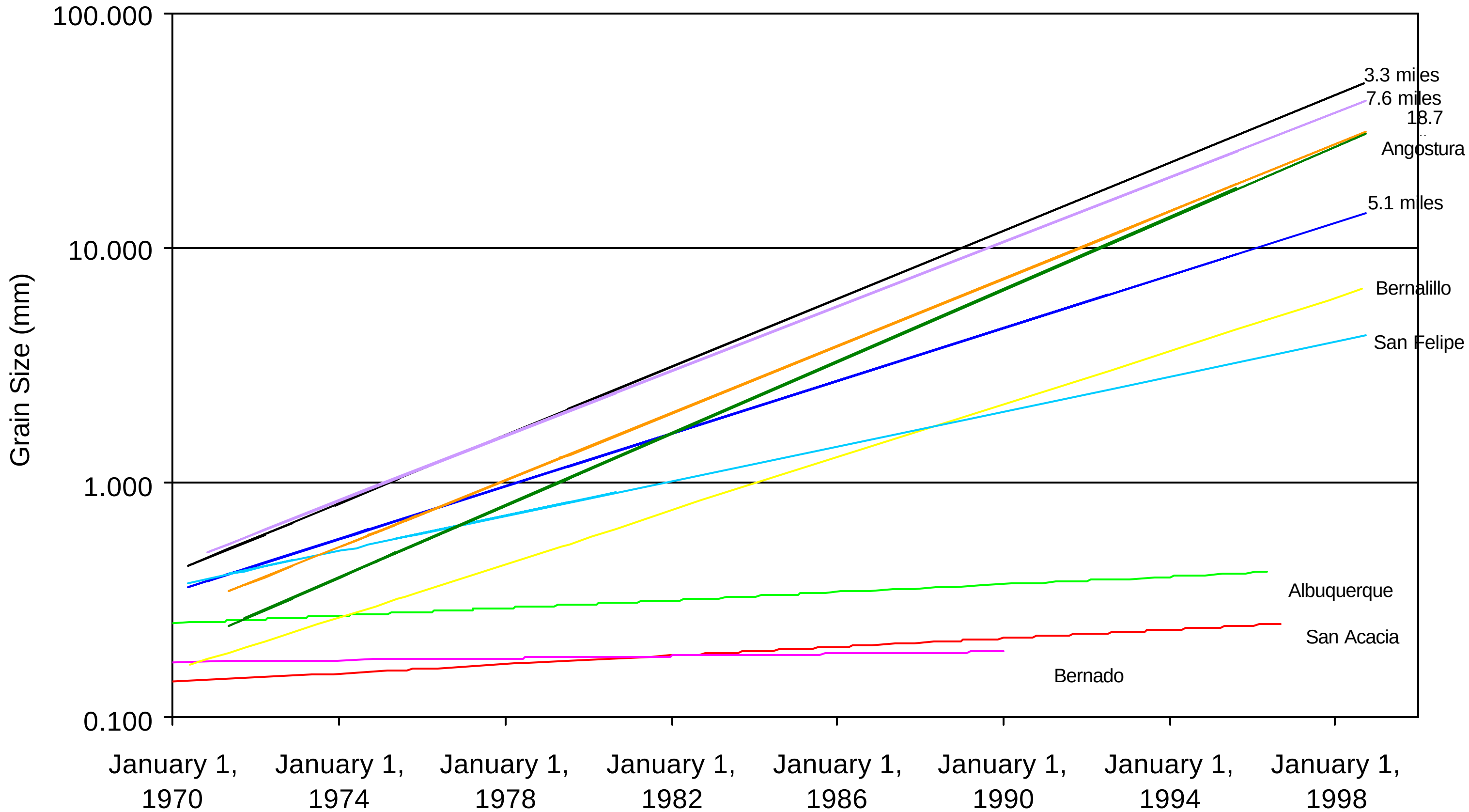


Figure 3.41. Regression lines showing changes of the D_{50} of the bed material between 1970 and 1998 for gage locations and other identified USBR range lines within the project reach of the Rio Grande. Data collected after 1992 represent averages of 3 samples taken on the range line.

Table 3.4. Summary of bed material D_{50} values derived from regression equations (Figure 3.41) for identified locations on the Rio Grande between 1970 and 1998. Data collected after 1992 represent averages of 3 samples taken on the range lines; whereas, the data collected before 1992 represent a single sample on the range lines.

Location	D_{50} (mm)			
	1970	1976	1986	1998
3.3*	0.42	1.14	6.07	45.31
5.1*	0.34	0.74	2.72	12.94
7.6*	0.44	1.15	5.61	37.69
San Felipe	0.36	0.61	1.43	3.98
18.7*	0.27	0.73	3.82	27.71
Angostura	0.19	0.56	3.27	27.23
Bernalillo	0.16	0.35	1.28	6.13
Albuquerque	0.25	0.28	0.34	0.43
Bernardo	0.17	0.18	0.19	0.20
San Acacia	0.14	0.16	0.20	0.26

*River miles below Cochiti Dam.

Table 3.5. Summary of bed-material gradation parameters for samples collected along the Middle Rio Grande by MEI in September 2001.

Sediment Sample Number	Location (RM)	D_{50} (mm)	D_{16} (mm)	D_{84} (mm)	D_{100} (mm)
1	RG u/s Rio Puerco (126.9)	0.3	0.2	0.6	2
2	RG d/s Rio Puerco (126.8)	0.2	0.1	0.4	2
3	RG @ San Acacia Gage (116.2)	1.1	0.4	8.8	32
4	RG @ Corky's Bluff, deeply incised reach (114.3)	0.8	0.3	2.3	18
5	Arroyo Alamillo	1.9	0.3	6.8	32
6	RG d/s Arroyo Alamillo, wide reach (112.2)	0.3	0.25	0.5	2
7	RG wide reach (111.1)	0.3	0.2	0.5	2
8	RG wide reach (108)	0.4	0.2	0.8	8
9	RG narrow reach (106.2)	0.4	0.3	0.6	18
10	RG narrow reach (105.4)	0.3	0.25	0.5	2
11	RG u/s N. Socorro Diversion Channel, narrow reach (103)	0.3	0.2	0.5	2
12	RG Socorro Bosque Park, narrow reach (101.9)	0.3	0.2	0.5	2
13	RG d/s of Arroyo Tio Bartolo, narrow reach (99.5)	0.4	0.2	0.5	4
14	RG @ mouth of Arroyo del Tajo (97.2)	0.3	0.2	0.4	1
15	RG d/s of Arroyo de las Canas, narrow reach (95.2)	0.3	0.2	0.4	8
16	RG d/s of Brown Arroyo, wide reach (92.5)	0.3	0.2	0.5	4
17	RG narrow reach (91)	0.3	0.2	0.4	2
18	RG wide reach (89.3)	0.3	0.2	0.5	4
19	RG narrow reach (87.4)	0.3	0.2	0.5	2
20	RG @ Albuquerque Gage (183.4)	0.6	0.3	18.9	64
WC1	RG @ mouth of Arroyo de la Parida (104.8)	32.2	16.6	70.8	128
WC2	RG d/s of Rio Salado (118.3)	56.2	33.3	88.7	256

mm, and the D_{84} has increased from about 0.7 to 9 mm. Although the D_{50} value appears to have increased, it is still well within the sand range, and the D84 value is consistent with that from previous samples. A number of gravel-covered bars are located between the dam and the gage, and the gravel seems to have been derived from flushing of sediment deposits from upstream of the dam. The most likely source of the gravels is the Rio Salado (Plate A.23) and erosion of older Rio Grande terrace sediments at the confluence.

Bed-material samples were collected up- and downstream of the Rio Puerco confluence (S1 and S2, respectively) to evaluate the assertion that the bed of the river between the Rio Puerco and San Acacia is coarsening (Baird, 2001), and to determine whether the Rio Puerco was the source of any gravel for the Rio Grande. No gravel was observed in the bed of the Rio Puerco for a distance of about 2 miles upstream of the confluence with the Rio Grande, which is in accord with the observations of Nordin (1963). The D_{50} of the upstream bed-material sample (S1) in the Rio Grande was 0.3 mm, and that of the downstream sample (S2) was 0.2 mm. No evidence of gravel was found by digging in the bed of the river at a number of locations, either upstream or downstream of the confluence. There is no doubt that the Rio Salado introduces a significant amount of gravel- and cobble-sized sediment to the Rio Grande (Plate A.23). A series of coarse-grained bank-attached and mid-channel bars are present in the Rio Grande downstream of the confluence (Plate A.22), and a coarse-grained, gravel-cobble riffle is present at the head of each of the bars. Pebble count WC2 was conducted in the first riffle downstream of the confluence. The D_{50} of the bed material was 56.2 mm, and the D_{84} was 88.7 mm (Table 3.5). The maximum particle size recorded in the riffle was 256 mm. It appears, therefore, that coarse bed material is not present in the Rio Grande upstream of the Rio Salado confluence, but there is a significant amount of gravel in the bed of the river downstream of the confluence. Gravel from the Rio Salado is stored in the pool upstream of the San Acacia Diversion Dam, and is periodically flushed downstream, where it is appears in the bed-material samples collected at the USGS gage at San Acacia. Some fine gravel was sampled in the bed of the river about 1.1 miles downstream of the San Acacia Diversion Dam (S4). The D_{50} of the sample was 0.8 mm, and the D_{84} was 2.3 mm, and it is highly likely that the source of the gravel is material flushed from upstream of the diversion.

The bed of the Rio Grande at the confluence with Arroyo Alamillo is composed of gravel, cobbles and small boulders that have been delivered to the river by the tributary. Sample S5 was collected in the bed of the tributary just upstream of the mouth. The D_{50} was 1.9 mm, and the D_{84} was 6.8 mm, and the sample contained particles up to 64 mm in size. However, about 1 mile downstream of the tributary, the D_{50} of the bed material was 0.3 mm, and the D_{84} was 0.5 mm (S6), and no gravel was found in the bed of the river. Four additional samples were collected from the bed of the river between San Acacia and the bridge at Escondida (S7, S8, S9, S10). The sampling locations included wide and narrow reaches of the channel. D_{50} values ranged from 0.3 to 0.4 mm, and D84 values ranged from 0.5 to 0.8 mm, all well within the sand size range. At the mouth of Arroyo de la Parida, a coarse-grained fan has prograded out into the Rio Grande forming a constriction in the river, as well as a coarse-grained riffle that spans the entire channel of the Rio Grande. The riffle creates a local baselevel control (Plate A.28). Pebble count WC1 was conducted at this riffle, and the D_{50} of the bed material was 32.2 mm, and the D_{84} was 70.8 mm (Table 3.5). The largest measured particle in the riffle was 128 mm. Gravel derived from the arroyo was observed in the bed of the channel as a surface veneer at the Escondida Bridge, which is located about 0.3 miles downstream.

Between the Escondida Bridge and the mouth of Brown Arroyo (about 8.3 miles), 5 sediment samples (S11, S12, S13, S14, S15) were collected from the bed of the Rio Grande in locations that were above and below the 5 east bank tributaries (Arroyo de los Pinos, Arroyo Tio Bartolo, Arroyo de la Presilla, Arroyo del Tajo, Arroyos de las Canas), and in wider and narrower reaches. The D_{50} values of the samples ranged from 0.3 to 0.4 mm, and the D_{84} values ranged from 0.4 to 0.5 mm (Table 3.5). Very minor amounts of fine gravel ranging in size from 4 to 8 mm were present in the samples, but there was no evidence of a concentration of the coarser particles either at the bed surface or at depth (up to 3 feet) at any inspected location. However, significant concentrations of larger sizes of sediment were always present at the mouths of the tributary arroyos. For example, at the mouth of Arroyo de las Canas, the entire bed of the Rio Grande at the apex of the tributary fan was composed of gravel and larger sizes, up to 180 mm.

Four samples of bed material from the Rio Grande (S16,S17,S18,S19) were collected in both narrow and wide locations in the 6 miles between the mouth of Brown Arroyo and the Highway 380 Bridge at San Antonio, a reach that has few of the large eastside tributary arroyos. D_{50} values were all 0.3 mm, and the D_{84} values ranged from 0.4 to 0.5 mm (Table 3.5). The samples contained very minor amounts of very fine gravel up to 4 mm in size, and there was no evidence of gravel concentration on the bed of the river at any of the locations.

The sediment data collected by MEI do not support the contention that there is a coarsening trend in the bed material of the Rio Grande between the Rio Puerco confluence and the Rio Salado confluence (Baird, 2001). There is no doubt that the bed of the Rio Grande is coarser between the Rio Salado confluence and San Acacia, but this is a condition that is caused by the supply of coarse sediment by the Rio Salado, and has nothing to do with trends that may be attributed to the upstream dams. At the San Acacia gage, the coarser sediments can be related to flushing of the diversion dam, and the logical source for the gravels is the Rio Salado. The bed of the Rio Grande is coarser at the confluences with the eastside tributary fans. The eastside tributaries between San Acacia and San Antonio have always contributed coarser sediment to the Rio Grande, and will continue to do so, especially since many of them are located in reaches where the baselevel was lowered by channelization of the Rio Grande, which causes locally higher sediment transport capacities. However, even though the tributaries introduce coarser sediment to the Rio Grande, the effect on the bed-material gradation of the Rio Grande is very local. There is no evidence to suggest that the bed of the Rio Grande between San Acacia and San Antonio is becoming coarser, or armored, and the bed-material gradation data show that the bed of the Rio Grande in this reach is composed of sand.

3.3.2. Sediment Transport Analysis

An analysis of the available sediment-transport data collected at gages along the Middle Rio Grande was performed to assess the existing and historic sediment-transport conditions along the reach to assist in characterizing the existing condition of the river. Alluvial rivers tend to adjust their gradient, planform, and cross-sectional shape toward a state of dynamic equilibrium between the sediment supply and the sediment-transport capacity (Schumm, 1977). Human activities, including the construction and operation of dams, flow diversion, installation of bank protection and grade controls, and changes in land-use alter the quantity and timing of water and sediment movement through the river system. This, in turn, causes the river to adjust toward a new equilibrium condition, subject to limitations on adjustability associated with man-made and geologic controls. Such changes have undoubtedly occurred in the Middle Rio Grande during the past century with the construction of the Federal dams, development of the irrigation and municipal water-supply systems, and changes in watershed land use, and in many cases, the adjustments continue to occur.

The Middle Rio Grande has one of the highest sediment loads of any river in the world, with measured sediment concentrations as high as 200,000 ppm (mg/l), but the average annual concentrations are reported to have fallen from 24,000 ppm in the 1950s to about 5,000 ppm at present (Baird, 1998). Practical and research interest in the behavior of the Rio Grande has led to the completion of numerous previous investigations of sediment transport in the Middle Rio Grande (Rittenhouse, 1944; Nordin and Dempster, 1963; Nordin and Beverage, 1965; Dewey et al., 1979; Baird, 1998; Leon, 1998; Bauer, 2000; Richard et al., 2000).

Discharge and sediment-load data were available for the USGS gages at Otowi Bridge, Cochiti Dam, San Felipe, Bernalillo, Albuquerque, Bernardo, San Acacia, and San Marcial. **Table 3.6** summarizes the period of record and number of sediment-transport measurements that are available at each location. In addition to the gage data, similar data were collected by the USGS at 38 cross sections between Cochiti Dam and the Isleta Diversion Dam between 1970 and 1975 (Dewey et al., 1979). For the gages downstream from Cochiti Dam, data collected before and after closure of the dam in 1973 were segregated to assist in evaluating the effects of sediment trapping in Cochiti Reservoir.

Suspended-Sediment Loads

Where available, daily suspended-sediment loads obtained from USGS records were used to develop suspended-sediment rating curves for the pre- and post-dam periods. These daily data were available for the pre-and post-Abiquiu periods at the Otowi gage (**Figure 3.42**), for the post-Cochiti Dam period at the below-Cochiti Dam gage (**Figure 3.43**), for the pre-Cochiti Dam period at the Bernalillo gage (**Figure 3.44**), and for both periods at the Albuquerque, Bernardo, San Acacia, and San Marcial gages (**Figures 3.45 through 3.48**). (Abiquiu Dam was closed in February 1963, and Cochiti Dam was closed in November 1973).

A series of 70 individual measurements were available for the pre-Cochiti period at the Rio Grande at Cochiti gage, and these measurements were used to develop the pre-Cochiti rating curve shown in Figure 3.43. Similarly, daily suspended-sediment data were not available at the San Felipe gage, but a series of 12 individual measurements that were taken between May 1970 and closure of Cochiti Dam in November 1973, and a series of 154 individual measurements that were taken after closure of Cochiti Dam are available (Table 3.6). These measurements were used to develop suspended-sediment rating curves for the San Felipe gage (**Figure 3.49**).

The rating curves for the Otowi gage (Figure 3.42) indicate that suspended-sediment loads in the range of flows up to about 500 cfs were similar during both the pre- and post-Abiquiu periods of records, but they decreased significantly at higher flows after closure of the Abiquiu Dam (Figure 3.42). Suspended-sediment loads at the below-Cochiti Dam gage also decreased significantly after closure of Cochiti Dam, with loads about an order-of-magnitude lower at low flows and two orders-of-magnitude lower at high flows (Figure 3.43). Similar trends occur at the other gages that were analyzed, with the difference between the pre- and post-Cochiti rating curves decreasing with increasing distance downstream from the dam (Figures 3.45 through 3.49).

Bed-Material Loads

One purpose of the sediment analysis is to evaluate changes in sediment load that may be responsible for adjustments in channel form. A significant portion of the suspended-sediment load that is discussed in the previous sections is wash load (i.e., material not found in significant quantities in the bed), and only a small part is bed-material load. Additionally, the majority of the bed-material load is not reflected in the suspended-sediment data, because most of this portion of the total sediment load is carried in contact with the bed or in the portion of the water-column that is below the intake of the suspended-sediment sampler. Since adjustments to the channel boundary are most closely related to the bed-material load, evaluation of the relationship between sediment load and channel form should be based on this portion of the total load.

Table 3.6. Summary of available data at USGS gage sites.

Gage Name	Station ID	Discharge Data	Suspended Sediment Data			Bed Material Data		
		Period of Record (mean daily flow)	Period of Record	Number of Measurements (pre-Cochiti)	Number of Measurements (post-Cochiti)	Period of Record	Number of Measurements (pre-Cochiti)	Number of Measurements (post-Cochiti)
Rio Grande at Otowi Bridge, NM	08313000	2/1/1895-9/30/99	10/1/55-9/30/95	NA	NA	NA	NA	NA
Rio Grande at Cochiti, NM	08314500	6/1/26-9/30/70	3/11/54-6/22/61	70	NA	NA	NA	NA
Rio Grande below Cochiti Dam, NM	08317400	10/1/70-9/30/99	7/1/74-9/30/88	0	56	NA	NA	NA
Rio Grande at San Felipe, NM	08319000	1/1/27-9/30/99	5/19/70-8/27/96	12	154	5/13/70-11/14/75[1]	106	31
Rio Grande at Bernalillo, NM	08329500	10/1/41-9/30/69	10/1/55-9/30/69	114	0	11/18/68-9/22/69	15	0
Rio Grande at Albuquerque, NM	08330000	10/1/42-9/30/99	10/1/69-9/30/95	96	406	5/8/69-9/1/87	66	190
Rio Grande Floodway at Bernardo, NM	08332000 08332010	10/1/55-9/30/99	10/1/55-9/30/95	59	349	4/8/69-9/2/87	16	129
Rio Grande Floodway at San Acacia, NM	08354500 08354900	7/1/46-9/30/99	7/1/46-9/30/96	145	393	5/14/68-6/3/87	20	88
Rio Grande Floodway at San Marcial, NM	08358400 08358500	7/1/46-9/30/99	7/1/46-10/1/56	86	454	5/14/68-6/3/87	27	151

[1]Measurements from USGS channel adjustment cross sections

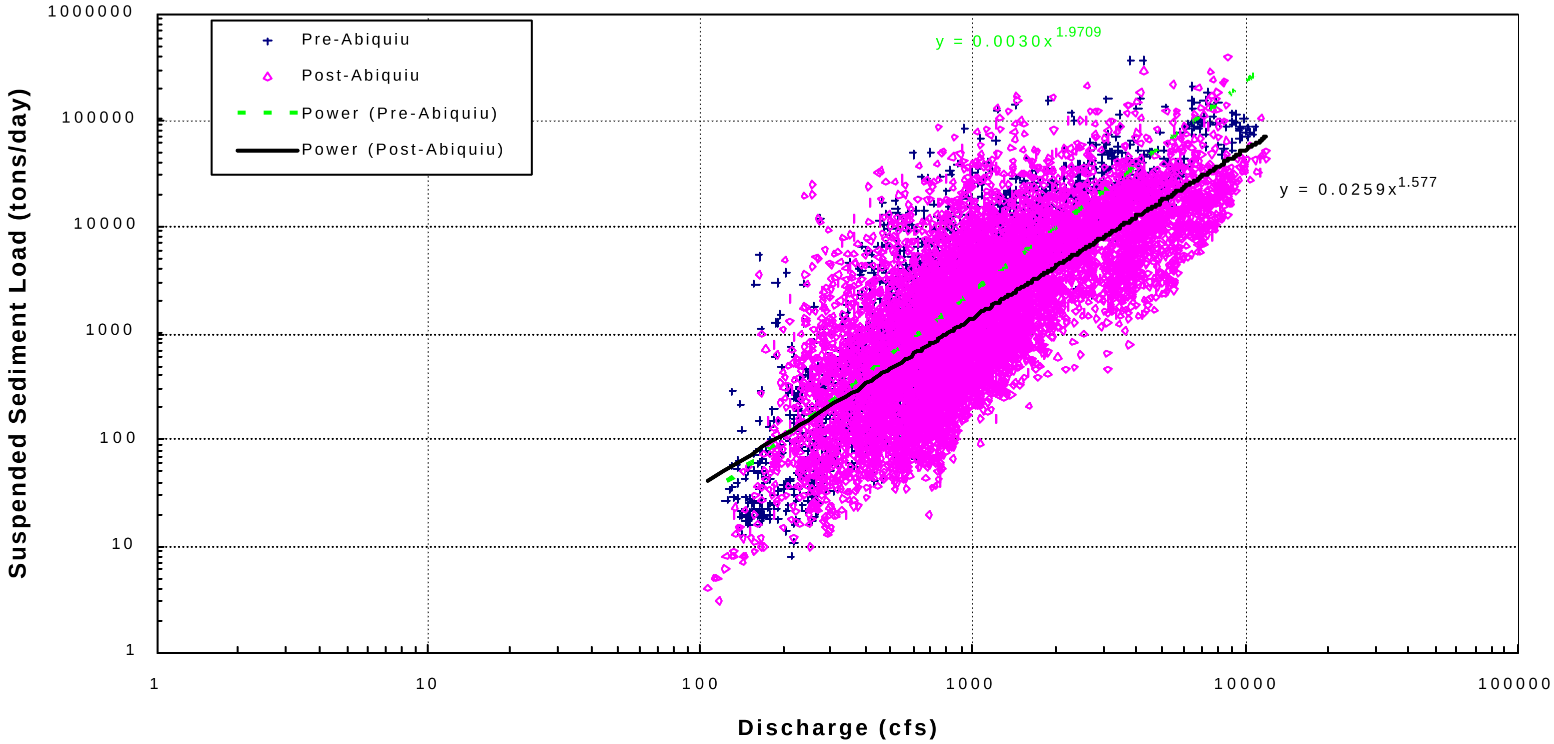


Figure 3.42. Suspended-sediment rating curves for the Rio Grande at Otowi Bridge gage, pre- and post-Abiquiu periods (1956-February 1963; March 1963-1999).

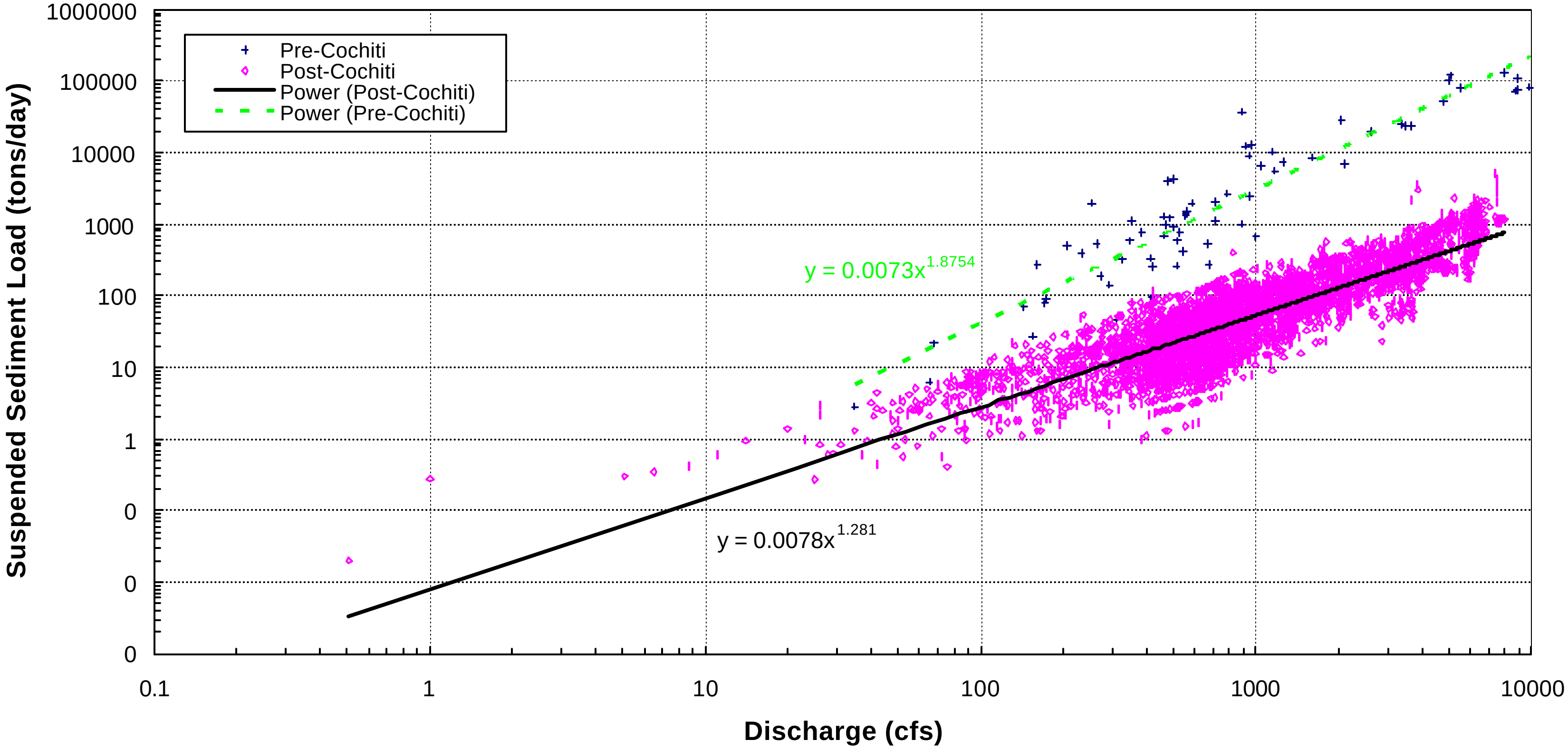


Figure 3.43. Suspended-sediment rating curves for the pre-Cochiti Dam period at Cochiti gage (individual measurements taken from Nordin, 1965), and for the post-Cochiti Dam period at the below Cochiti Dam gage (USGS daily values November 1973-1999).

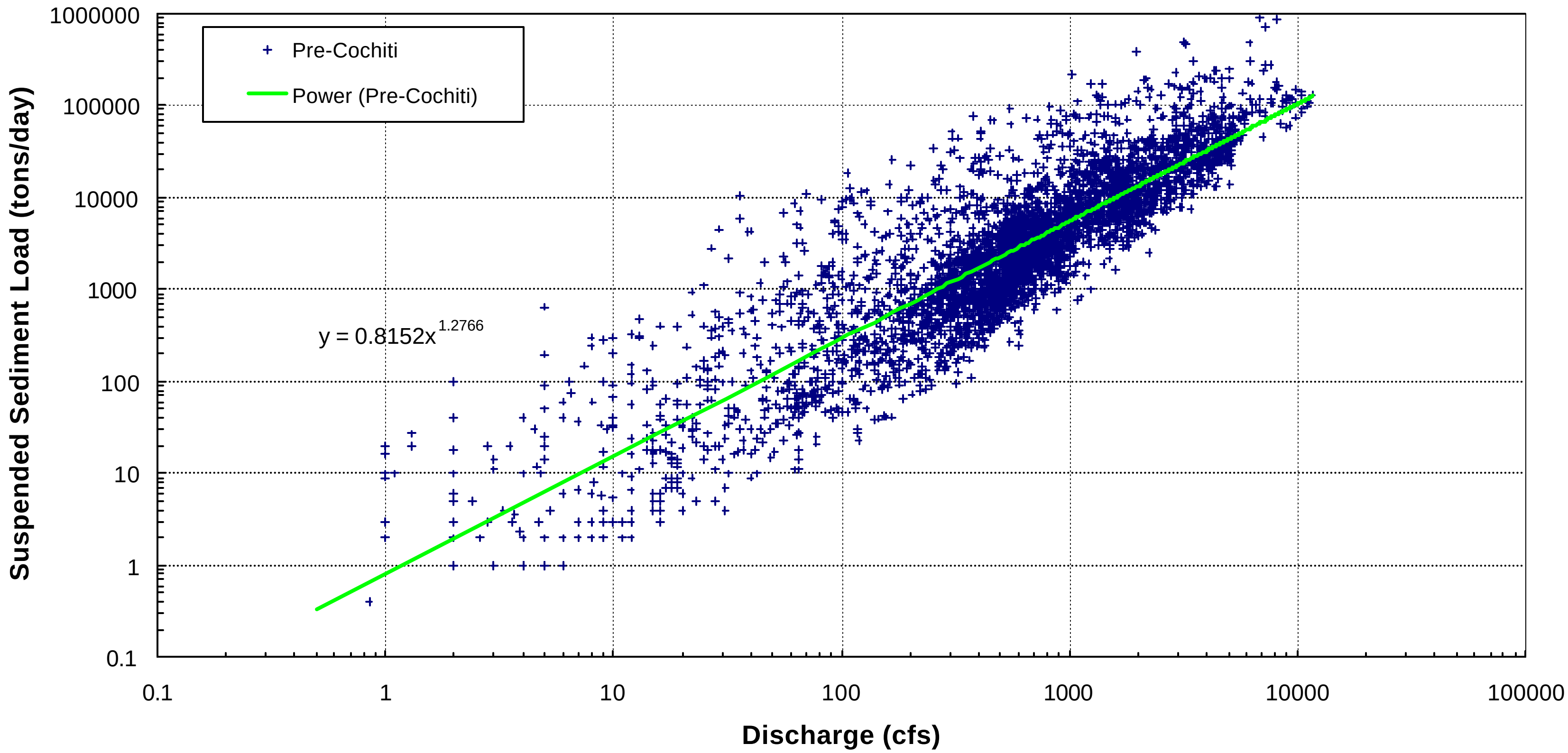


Figure 3.44. Suspended-sediment rating curves for the pre-Cochiti Dam period at the Bernalillo gage (USGS daily values, 1956-1969).

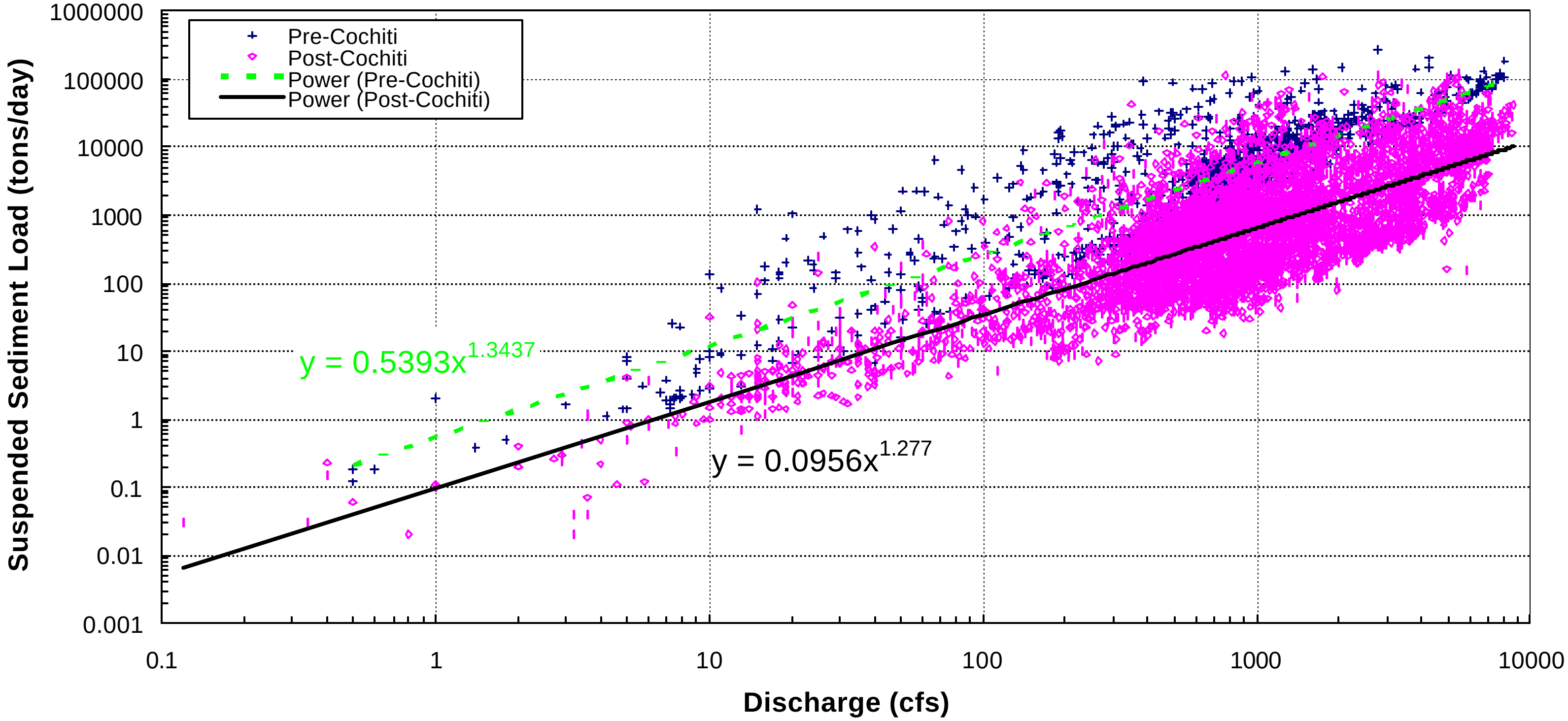


Figure 3.45. Suspended-sediment rating curves for the pre- and post-Cochiti Dam periods for the Albuquerque gage (USGS daily values, 1970-October 1973; November 1973-1995).

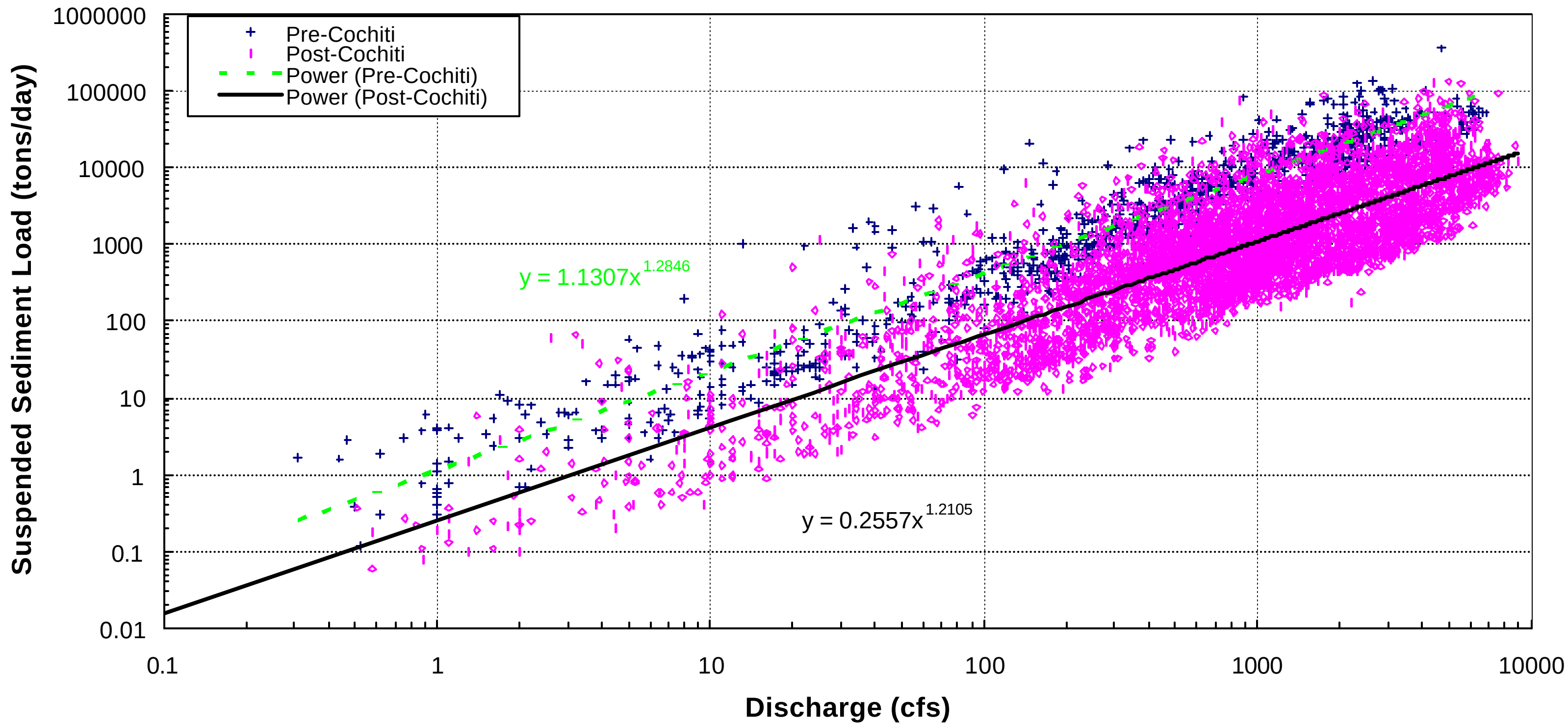


Figure 3.46. Suspended-sediment rating curves for the pre- and post-Cochiti Dam periods at the Bernardo gage (USGS daily values, 1965-October 1973; November 1973-1995).

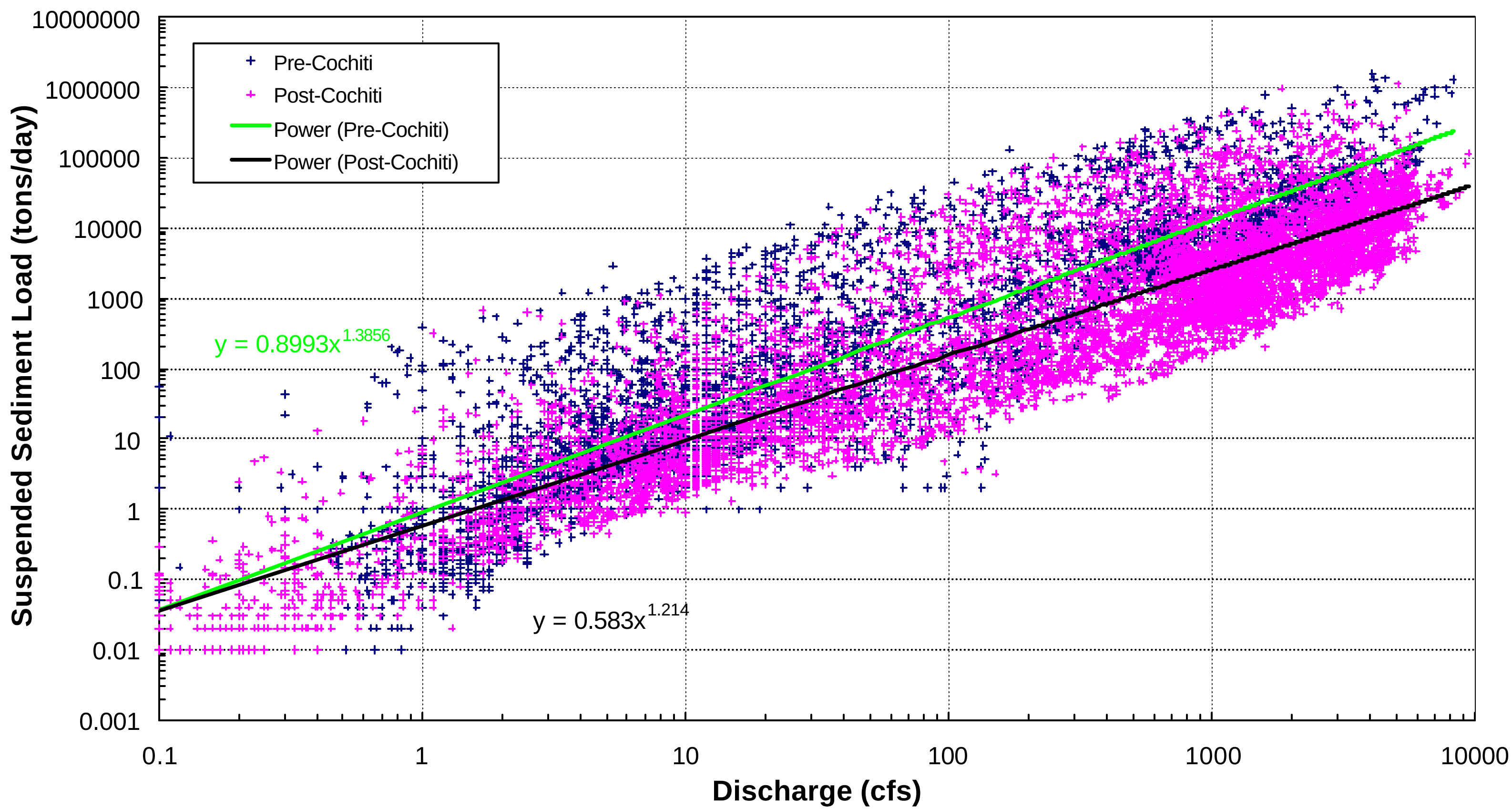


Figure 3.47. Suspended-sediment rating curves for the pre- and post-Cochiti Dam periods at the San Acacia gage (USGS daily values, July 1946-October 1973; November 1973-1996).

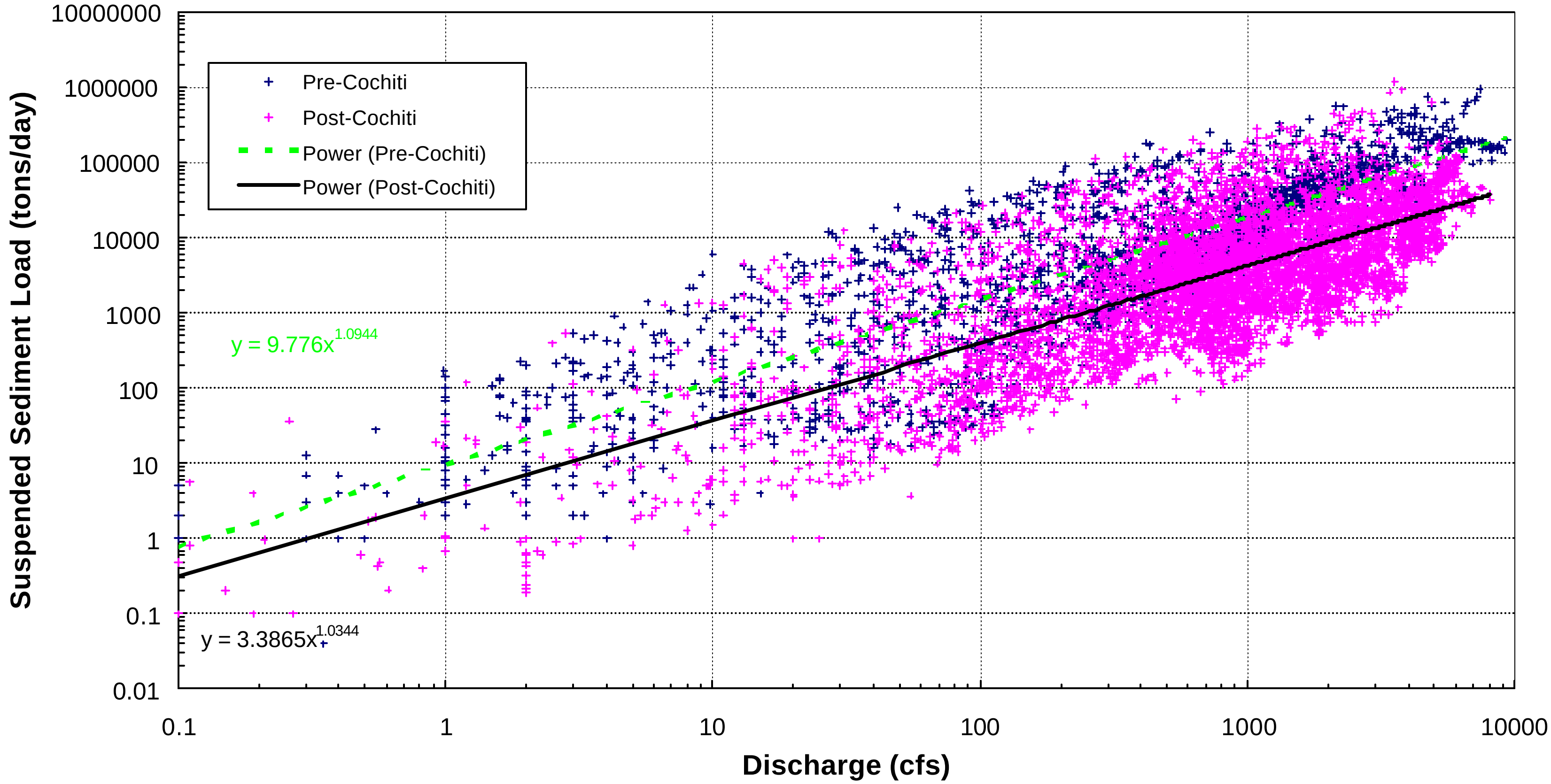


Figure 3.48. Suspended-sediment rating curves for the pre- and post-Cochiti Dam periods at the San Marcial gage (USGS daily values, July 1946-October 1973; November 1973-1995).

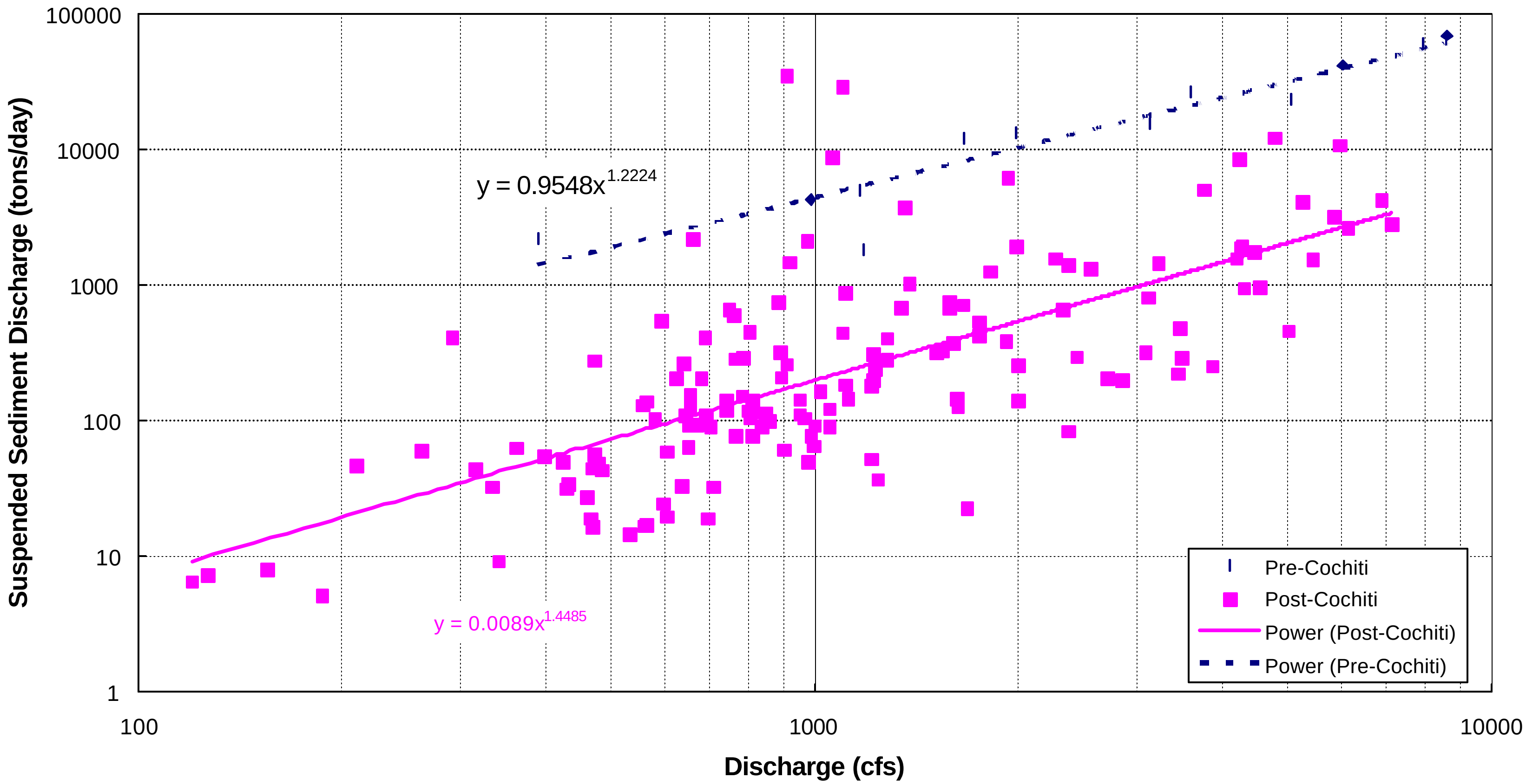


Figure 3.49. Suspended-sediment rating curves for the pre- and post-Cochiti Dam periods at San Felipe (USGS point measurements, May 1970-October 1973; November 1973-November 1975).

Bed-material transport rating curves were developed by combining the available USGS suspended-sediment and bed-load measurements. This was accomplished by adjusting the suspended-sediment data to remove the particle sizes in the silt/clay size range (i.e., smaller than 0.062 mm). The resulting suspended bed-material load was added to the concurrent bed-load measurement to obtain the total bed-material load. Bed-material rating curves were developed in this manner for the pre- and post-Cochiti Dam periods for the San Felipe, Albuquerque, Bernardo, San Acacia, and San Marcial gages, and for the pre-Cochiti Dam period for the Bernalillo gage (**Figures 3.50 through 3.55**).

Data required to calculate bed-material load were not available for the Rio Grande at Cochiti gage for the pre-Cochiti period. Because of the lack of comparable measured data, the bed-material rating curves developed by Nordin and Beverage (1965) were used in subsequent computations. The equation for this curve is:

$$Q_s = 0.00361Q^{1.98} \tag{3.1}$$

where Q_s is the bed-material load in tons per day and Q is the discharge in cfs.

The changes in both the suspended-sediment and bed-material rating curves at Cochiti, San Felipe, Albuquerque and Bernardo are attributable primarily to the impacts of the upstream dams. Rittenhouse (1944) and Happ (1948) concluded that about 19 percent of the total sediment load in the Middle Rio Grande was derived from the Rio Grande above Cochiti (primarily the Rio Chama), about 1 percent was derived from the Santa Fe River, about 3 percent was derived from Galisteo Creek, and about 12 percent was derived from the Jemez River, for a total of about 35 percent. Elimination of these sources undoubtedly had a major impact on the sediment loads in the river.

The reasons for the reduction in bed-material load at the Bernardo gage are less obvious. The channel at the gage, and upstream as far as the Isleta Diversion, is clearly braided and has a sand bed which suggests that the channel at Bernardo is unlikely to be supply-limited with respect to the bed-material load. However, channelization and bank protection along the river upstream from the gage have eliminated a potentially important sediment source (i.e., bank erosion), which may have contributed to the reduction. The lack of change at San Acacia and San Marcial can be attributed to the sediment supplied by the Rio Puerco, Rio Salado and other lesser tributaries, as well as the relatively long reach of mainstem between these gages and the upstream gages, that were estimated to supply about 65 percent of the sediment (Rittenhouse, 1944; Happ, 1948). The reduction in the supply of sediment from the Rio Puerco as the incised channel has evolved to a condition that promotes sediment storage (Schumm et al., 1984; Gellis et al., 1991) means that the supply, even to the lower reaches of the river, has been reduced over time (USBR, 1992).

Suspended-Sediment Concentrations

Average annual suspended-sediment concentrations were estimated for the pre- and post-dam periods at each of the gages where sufficient data were available (**Table 3.7**). The estimates were made by dividing the total sediment load for the period of record by the total runoff volume, taking into account the appropriate conversion factors required to present the results as ppm or mg/l.

At all of the gages that were considered, including the Otowi gage, the average concentrations decreased significantly after closure of Cochiti Dam. As expected, the most dramatic decrease occurs at the Cochiti and San Felipe gages, where the post-dam concentrations were about 1.2 and 5.4 percent of the pre-dam concentrations, respectively. At the Albuquerque, Bernardo and San Acacia gages, the post-dam concentrations were 20 percent of the pre-dam values, and were about

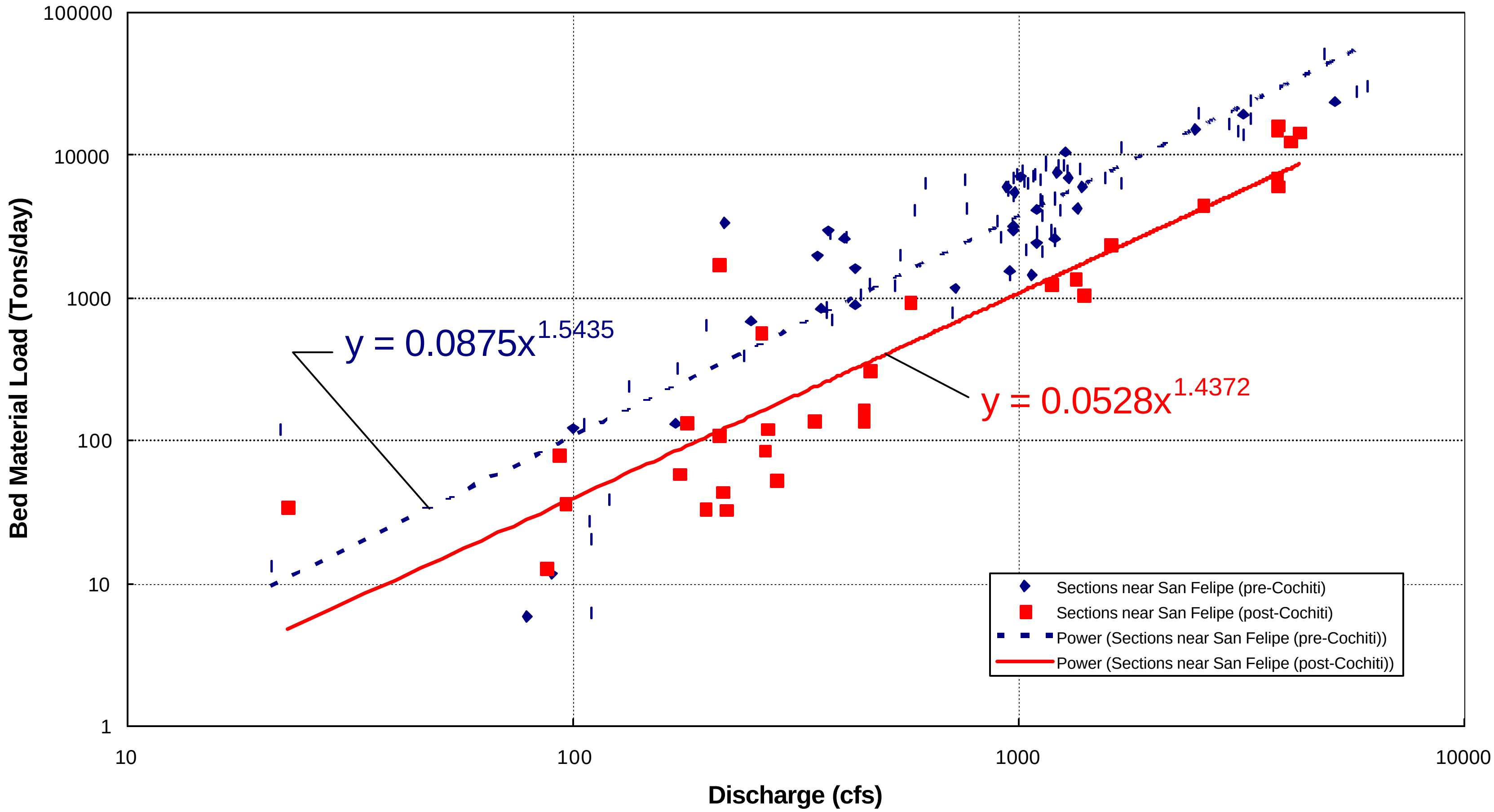


Figure 3.50. Bed-material rating curves for the pre- and post-Cochiti Dam periods at the USGS Channel Adjustment Cross Sections near San Felipe.

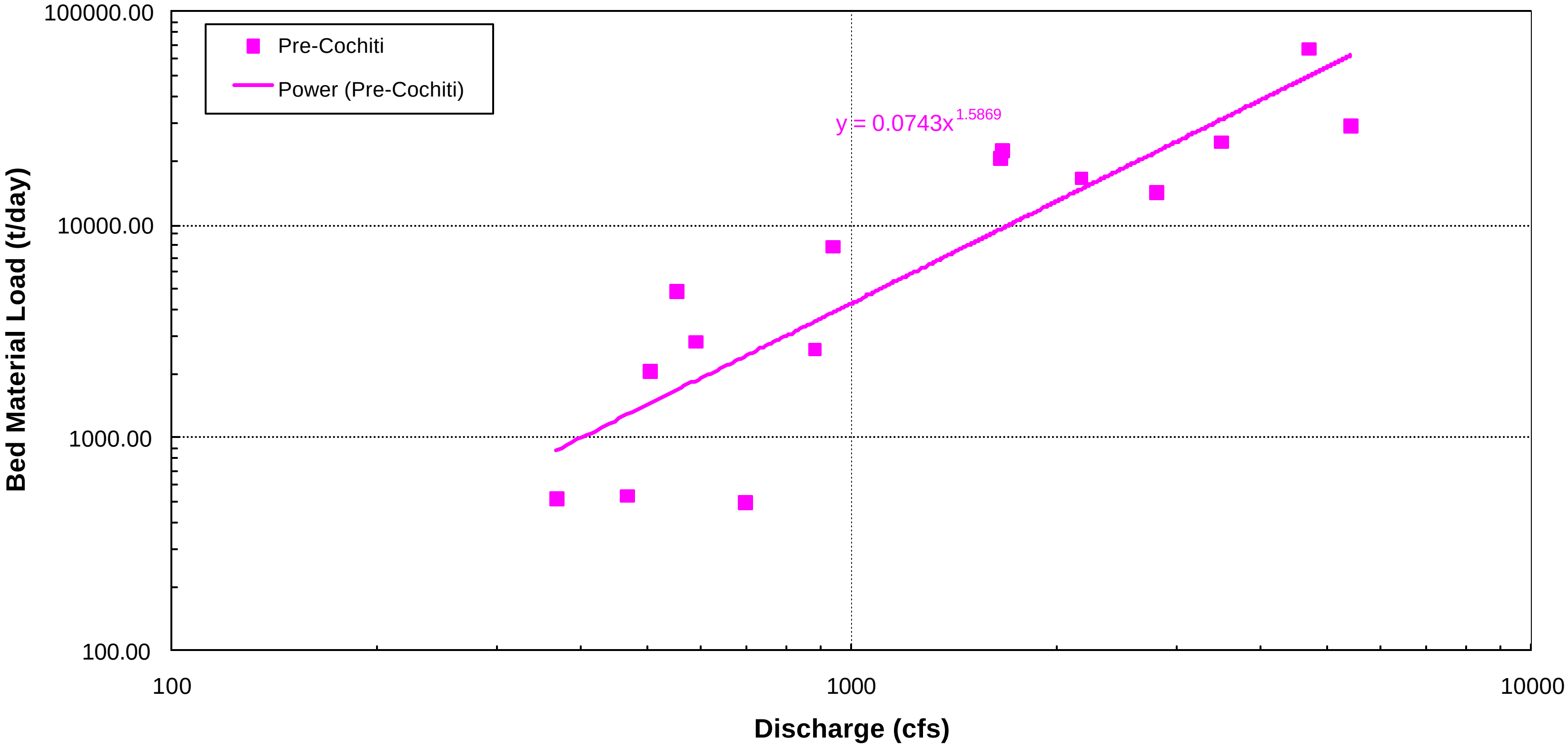


Figure 3.51. Bed-material-rating curve for the pre-Cochiti Dam period at the Bernalillo gage.

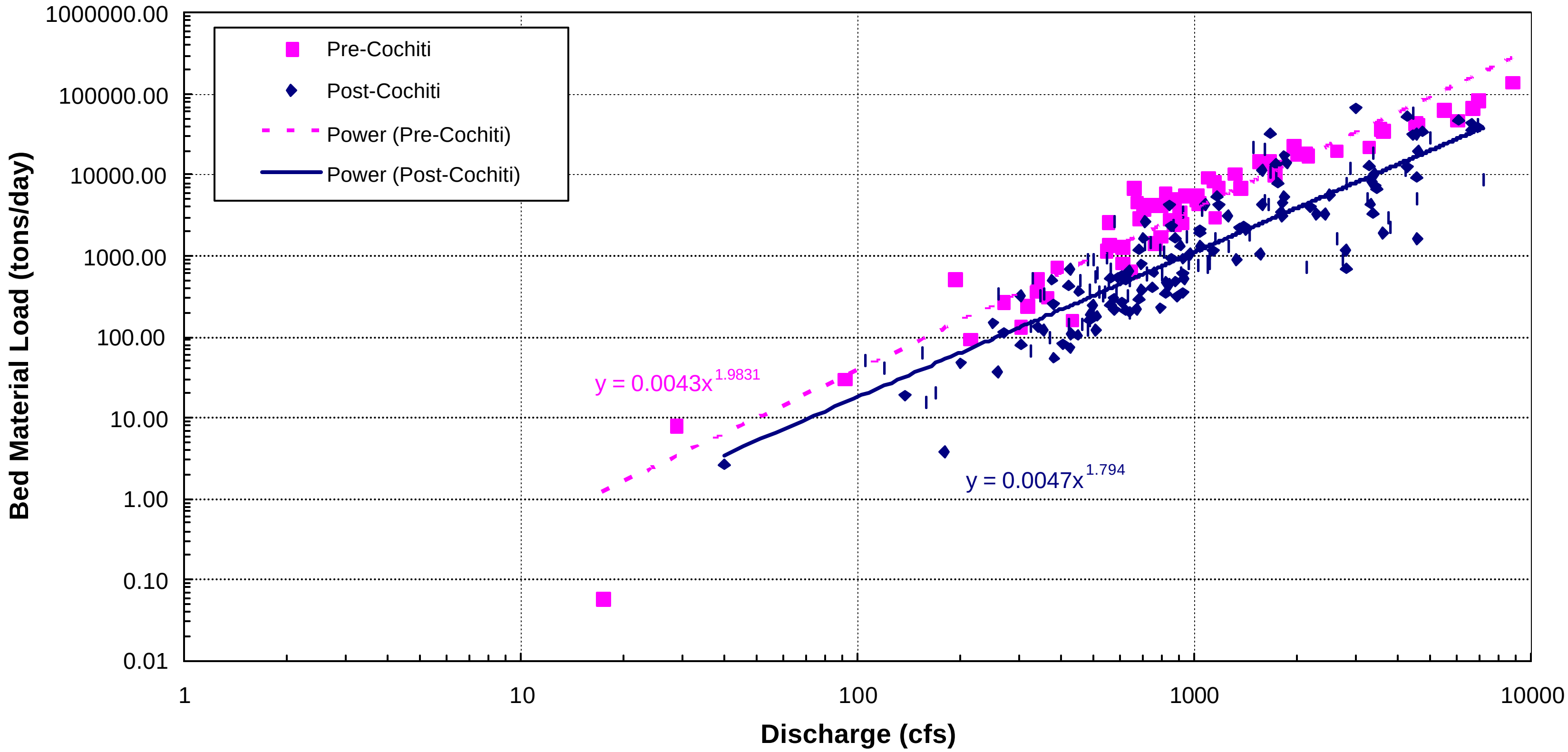


Figure 3.52. Bed-material rating curves for the pre- and post-Cochiti Dam periods at the Albuquerque gage.

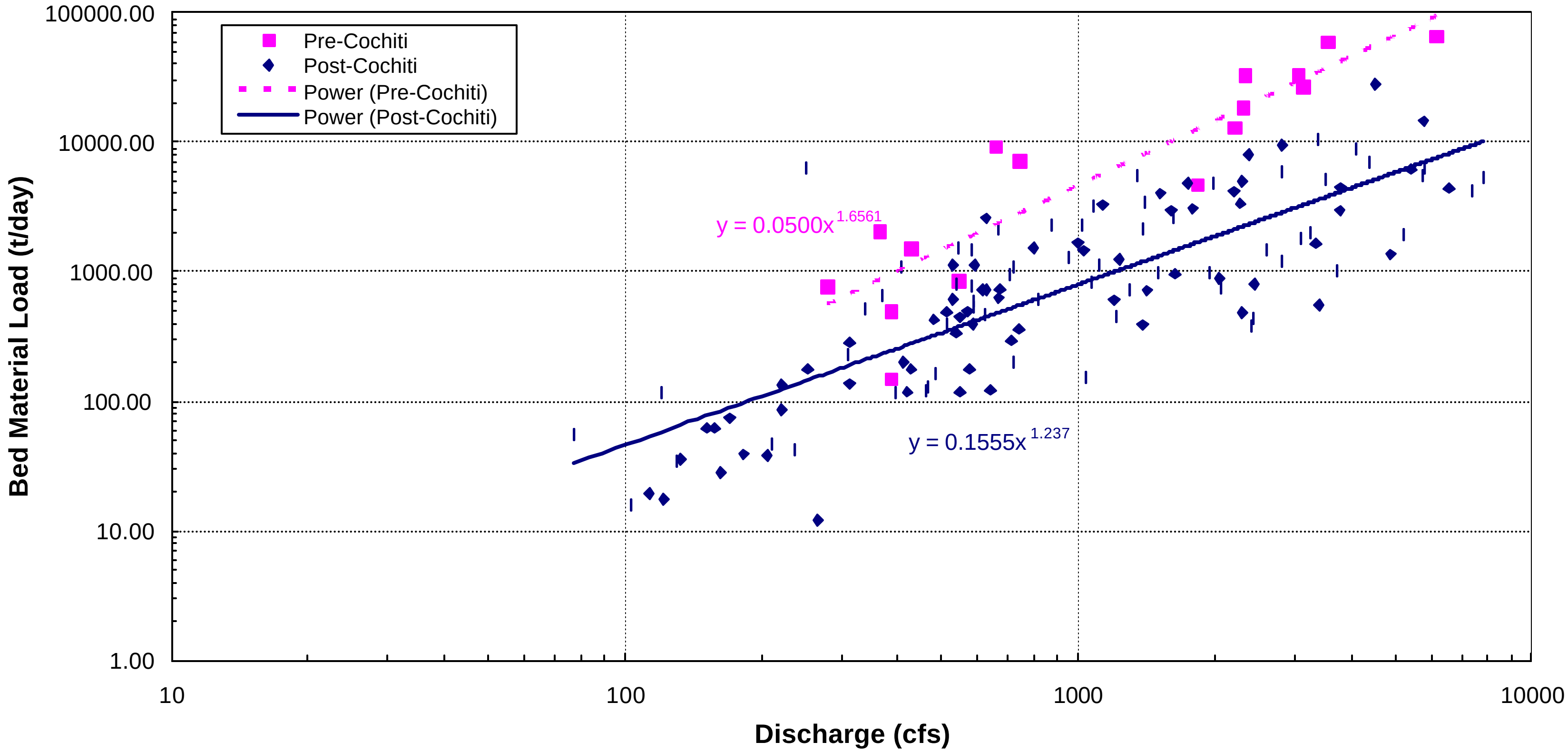


Figure 3.53. Bed-material rating curves for the pre- and post-Cochiti Dam periods at the Bernardo gage.

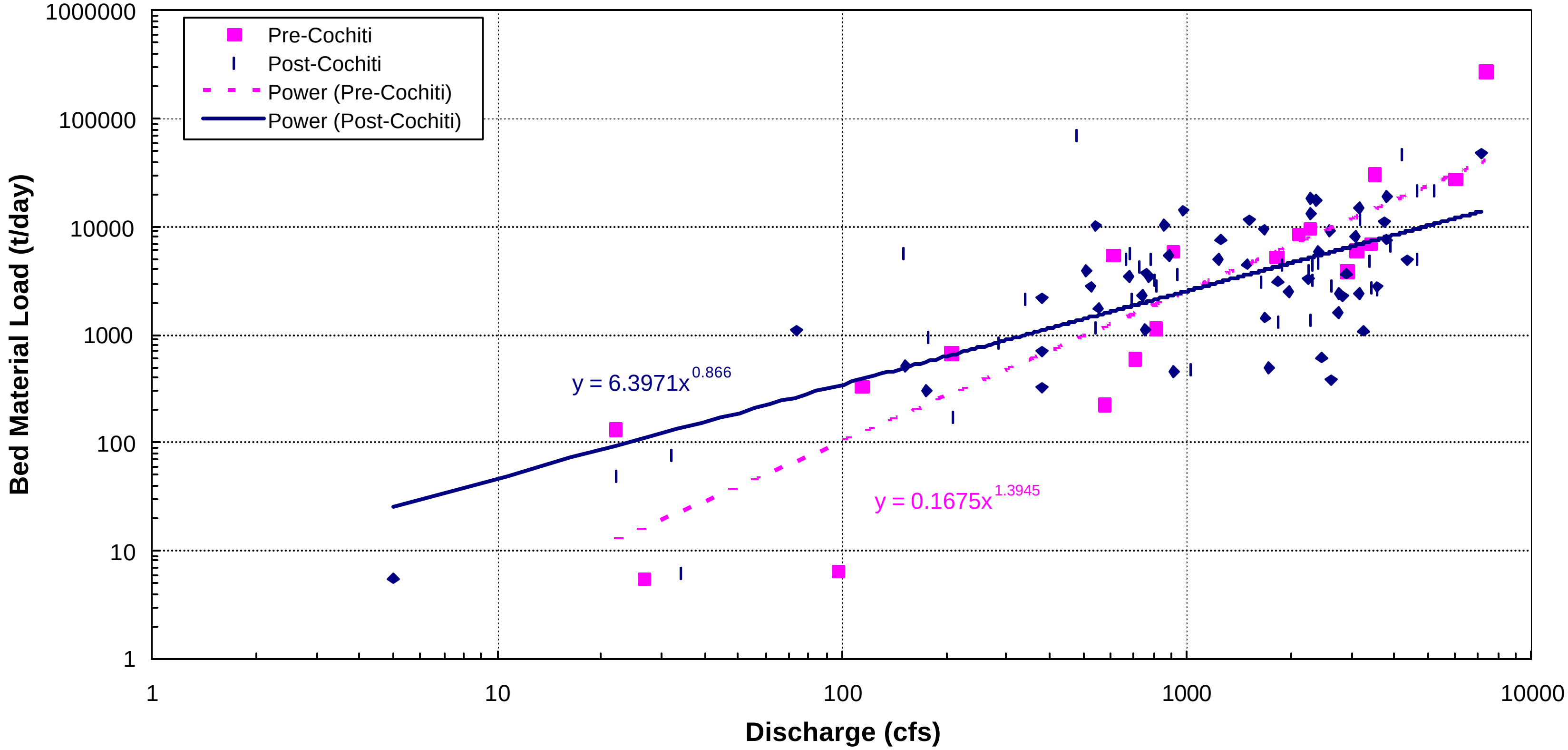


Figure 3.54. Bed-material rating curves for the pre- and post-Cochiti Dam periods at the San Acacia gage.

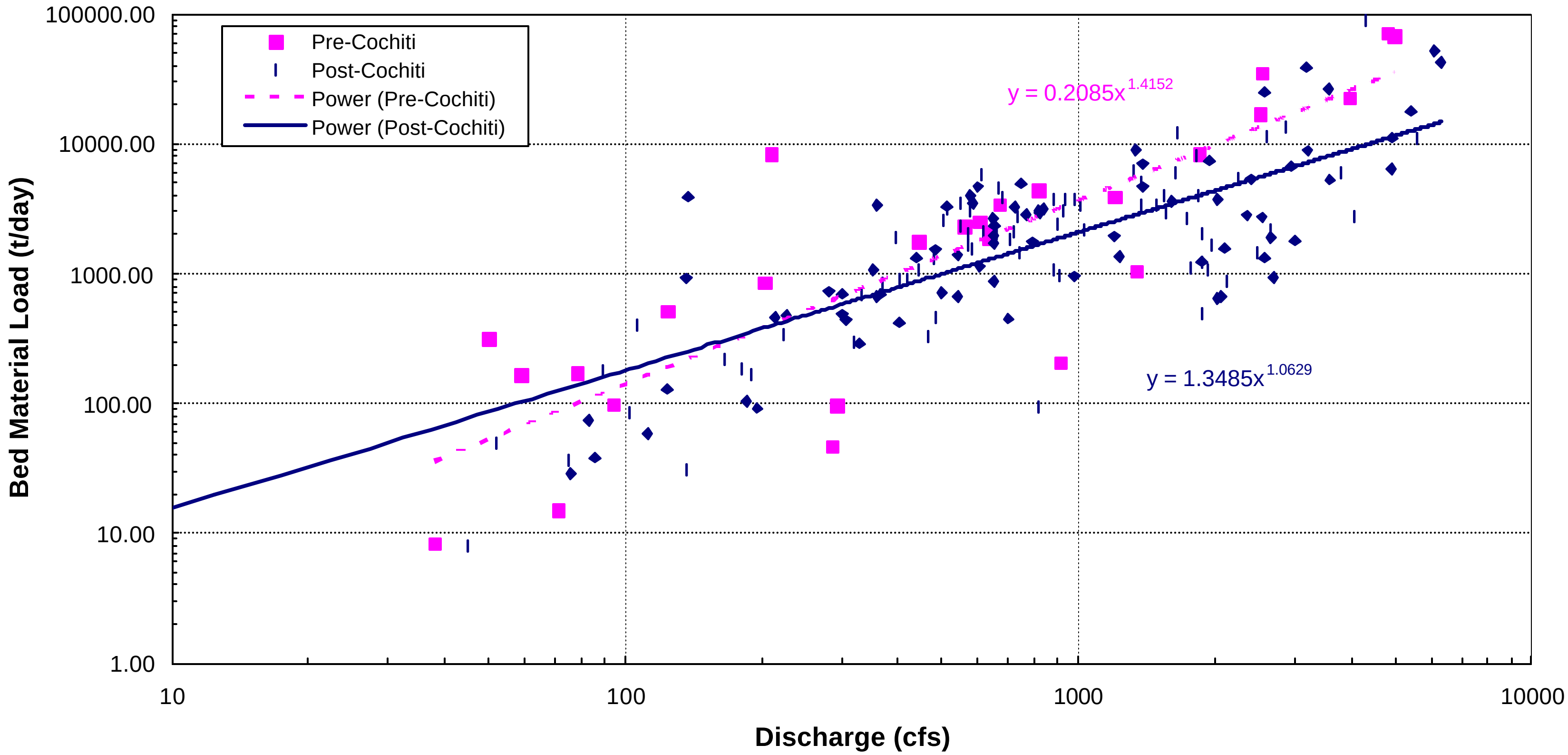


Figure 3.55. Bed-material rating curves for the pre- and-post Cochiti Dam periods at the San Marcial gage.

30 percent at the San Marcial gage. For comparison purposes, the average suspended-sediment concentrations for the pre- and post-Cochiti Dam periods are also shown for the Otowi gage data, which is upstream from Cochiti Dam. At this location, the average concentration during the 1955 through 1973 period was about double the concentration between 1974 and 1995. Although Cochiti Dam is a very effective sediment trap, its highly likely, based on the Otowi gage data, that other watershed-related factors also affected the suspended-sediment loads at the below-Cochiti Dam gages during this period. In evaluating these results, it is important to note that the pre-dam periods of record vary among the gages, and in some cases (e.g., Albuquerque and Bernardo), are relatively short (Table 3.6). For the post-dam period, most of the records cover the same basic time-period (Table 3.6).

Table 3.7. Summary of annual suspended-sediment concentrations for pre- and post-Cochiti periods at gages on the Middle Rio Grande.

Gage Name	Station ID	Average Annual Suspended-Sediment Concentration (mg/L)	
		Pre-Cochiti (Period of Record)	Post-Cochiti (Period of Record)
Rio Grande at Otowi Bridge, NM	08313000	2,160 (1955-73)	1,160 (1974-95)
Rio Grande at Cochiti, NM	08314500	3,310 (1926-73)*	40 (1974-88)
Rio Grande at San Felipe, NM	08319000	2,020 (1927-73)*	110 (1973-99)*
Rio Grande at Bernalillo, NM	08329500	4,190 (1956-73)	---
Rio Grande at Albuquerque, NM	08330000	3,850 (1970-73)	740 (1974-95)
Rio Grande Floodway at Bernardo, NM	08332010	4,190 (1965-73)	860 (1974-95)
Rio Grande Floodway at San Acacia, NM	08354500 08354900	14,200 (1946-73)	2,990 (1974-96)
Rio Grande Floodway at San Marcial, NM	08358400 08358500	12,700 (1946-73)	3,790 (1974-95)

*From Nordin and Beverage (1965)

The post-dam data shown in Table 3.7 indicate that the average suspended-sediment concentration increases progressively in the downstream direction from about 40 ppm downstream from Cochiti Dam to about 3,800 ppm at San Marcial. The most dramatic increase along the river occurs between the Bernardo and San Acacia gages, most likely due to inflows from the Rio Puerco and Rio Salado, which both contribute a significant amount of sediment. Part of the change from pre- to post-dam periods at the San Acacia and San Marcial gages may also be due to the documented reduction in average concentrations in the Rio Puerco. The USBR (1992), as cited in Crawford et al. (1993) reported average concentrations in the Rio Puerco near the mouth of 152,000 mg/l for the period 1956 to 1961, decreasing to 92,000 mg/l during the period 1977 to 1984.

Grain-size analysis of suspended-sediment and bed-material samples collected in the Rio Puerco (Nordin, 1963) show that the bulk of the suspended sediments (65 to 95 percent) are composed of silt and finer sizes (<0.0625 mm), and a significant portion of the bed-material samples (30 to 85 percent) are also composed of silt- and finer-sized sediments. Significant reductions in the average sediment concentrations have occurred in the Rio Puerco since the 1950s (Crawford et al., 1993) because the evolving incised channel again began to store sediments (Elliott, 1979; Schumm et al., 1984; Gellis et al., 1991). However, since the bulk of the sediments derived from the Rio Puerco are fine grained, they do not contribute significantly to the bed-material load that controls the in-channel morphological features such as braid bars. The historical supply of the finer-grained and more cohesive sediments was probably responsible for the somewhat sinuous channel morphology of the Rio Grande downstream of San Acacia (Schumm, 1963) and the present very narrow channel downstream of the Bosque del Apache National Wildlife Refuge. The presence of up to 8-foot high headcuts in the bed of the Rio Grande near San Marcial that formed in erosion-resistant silts and clays as a result of channel avulsions in the 1930s has also been attributed to the high concentrations of fine sediments delivered from the incision of the Rio Puerco (Happ, 1948).

Double-Mass Curves

Because data were not available to develop a quantitative sediment budget for the individual reaches of the Middle Rio Grande, double-mass curves were developed for each of the gages for which sufficient data were available to graphically show the cumulative quantity of sediment that was carried by the river past each gage as a function of the cumulative quantity of water (**Figures 3.56 through 3.62**). Only the suspended-sediment load is shown for the Otowi gage (Figure 3.56) and for the post-Cochiti Dam period at the Cochiti gage (Figure 3.57) because bed-material load data were not available. At all other gages, both the total sediment load and the suspended-sediment loads are shown (Figures 3.58 through 3.62). Changes in the slope of these curves reflect changes in the relative rate at which the sediment is moved through the system.

Except for Water Year 1995, the slope of the curve for the Otowi gage progressively decreases with time (Figure 3.56), indicating that watershed factors, including construction of upstream dams caused a progressive reduction in suspended-sediment load at that location. The reason for the sharp increase in slope in 1995 is not known, but is likely related to an upstream disturbance that increased the suspended-sediment concentration. Review of the daily sediment loads indicates that higher than normal suspended-sediment concentrations occurred between late-April and mid-July 1995.

At the Cochiti gage, the suspended-sediment curve has essentially no slope after closure of Cochiti Dam, reflecting the nearly 100 percent trap efficiency of the dam (Figure 3.57). At all of the other gages, both the suspended-sediment and total load curves flatten dramatically after closure of Cochiti Dam, again reflecting the high trap efficiency of the dam. Consistent with the average suspended-sediment concentrations discussed in the previous section, the slope of the suspended-sediment curves tends to increase in the downstream direction due to the increasing sediment contribution from tributaries that enter downstream from the dam. The slope of the total load curve is generally steeper than the suspended-load curve because of the inclusion of the bed-material load that is controlled by the hydraulic capacity of the river in the vicinity of the gage, and is not significantly affected by the supply from upstream. During the post-Cochiti Dam period, the slope of the lines is remarkably constant at each of the gages, indicating that the average sediment loads were very consistent from year-to-year.

Seasonal Variation In Sediment Load

Sediment transport in natural river systems typically exhibits a hysteresis behavior in which the sediment loads tend to be higher during certain portions of the hydrograph than at equivalent discharges during other portions of the hydrograph (Paustian and Beschta, 1979). A typical cause of this phenomenon is the accumulation of fine sediment in the channel due to deposition of aeolian sediment, contributions from tributaries and bank sloughing during low-flow periods, followed by entrainment of the accumulated material during the rising limb of the hydrograph. The resulting short-term sediment loads can thus be elevated above the normal loads. After the accumulated material is entrained, the sediment loads return to their normal levels. Other natural and man-

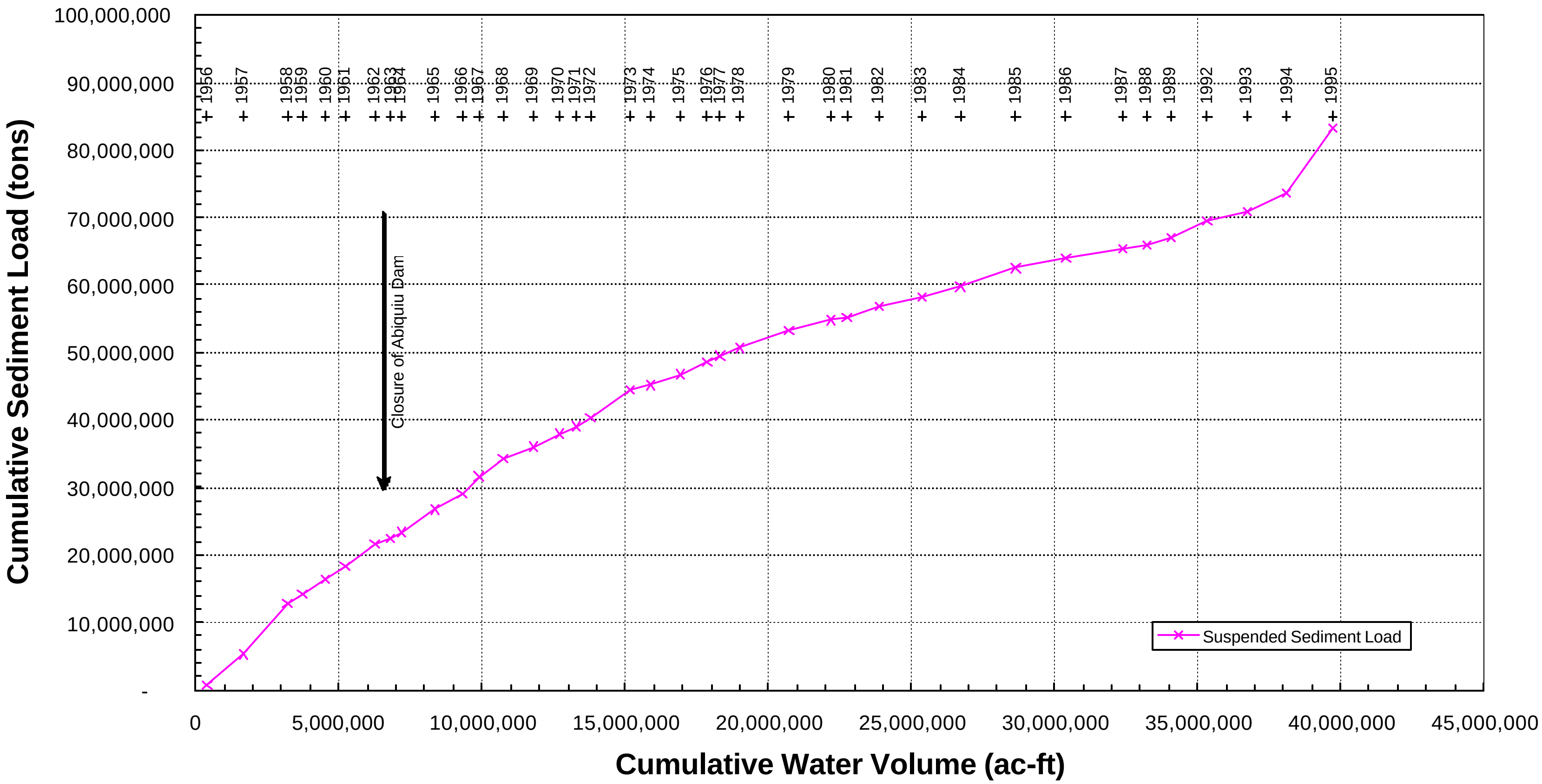


Figure 3.56. Cumulative quantity of suspended sediment that passed the Otowi gage as a function of cumulative water volume during the period 1956 through 1995.

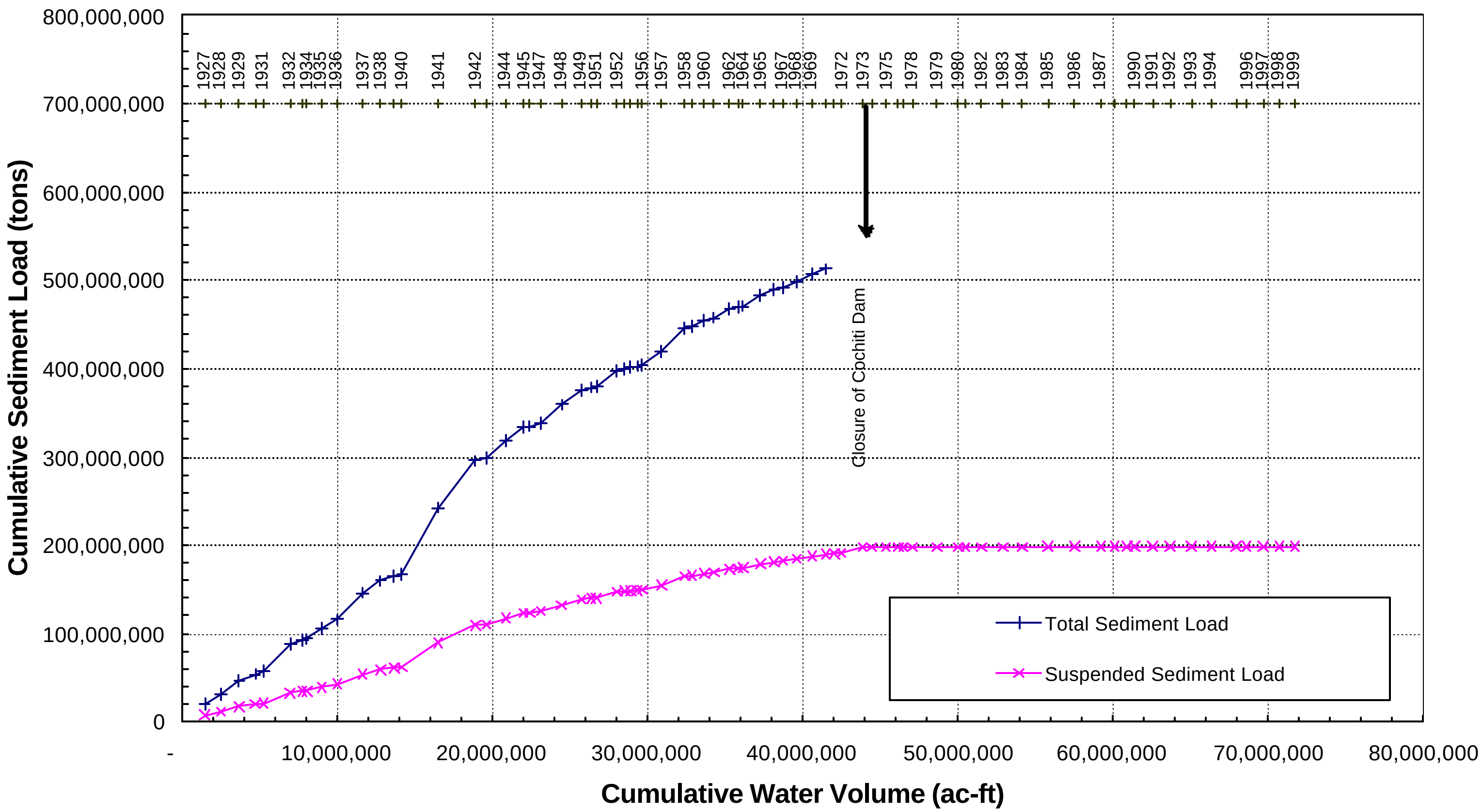


Figure 3.57. Cumulative quantity of total and suspended sediment that passed the Cochiti gage (at Cochiti gage prior to 1973, below Cochiti Dam after 1973) as a function of cumulative water volume during the period 1927 through 1999.

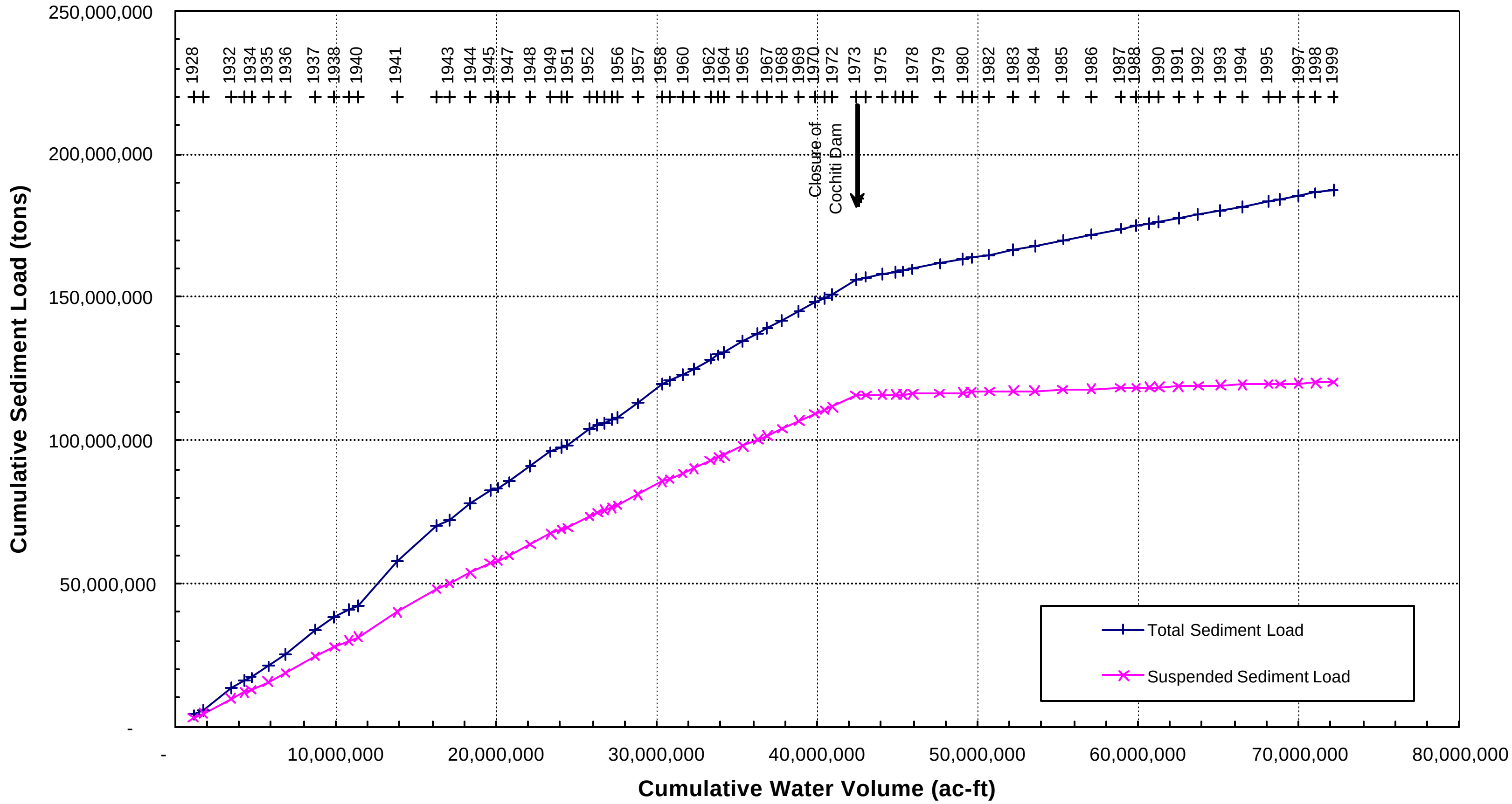


Figure 3.58. Cumulative quantity of total and suspended sediment that passed the San Felipe gage as a function of cumulative water volume during the period 1928 through 1999.

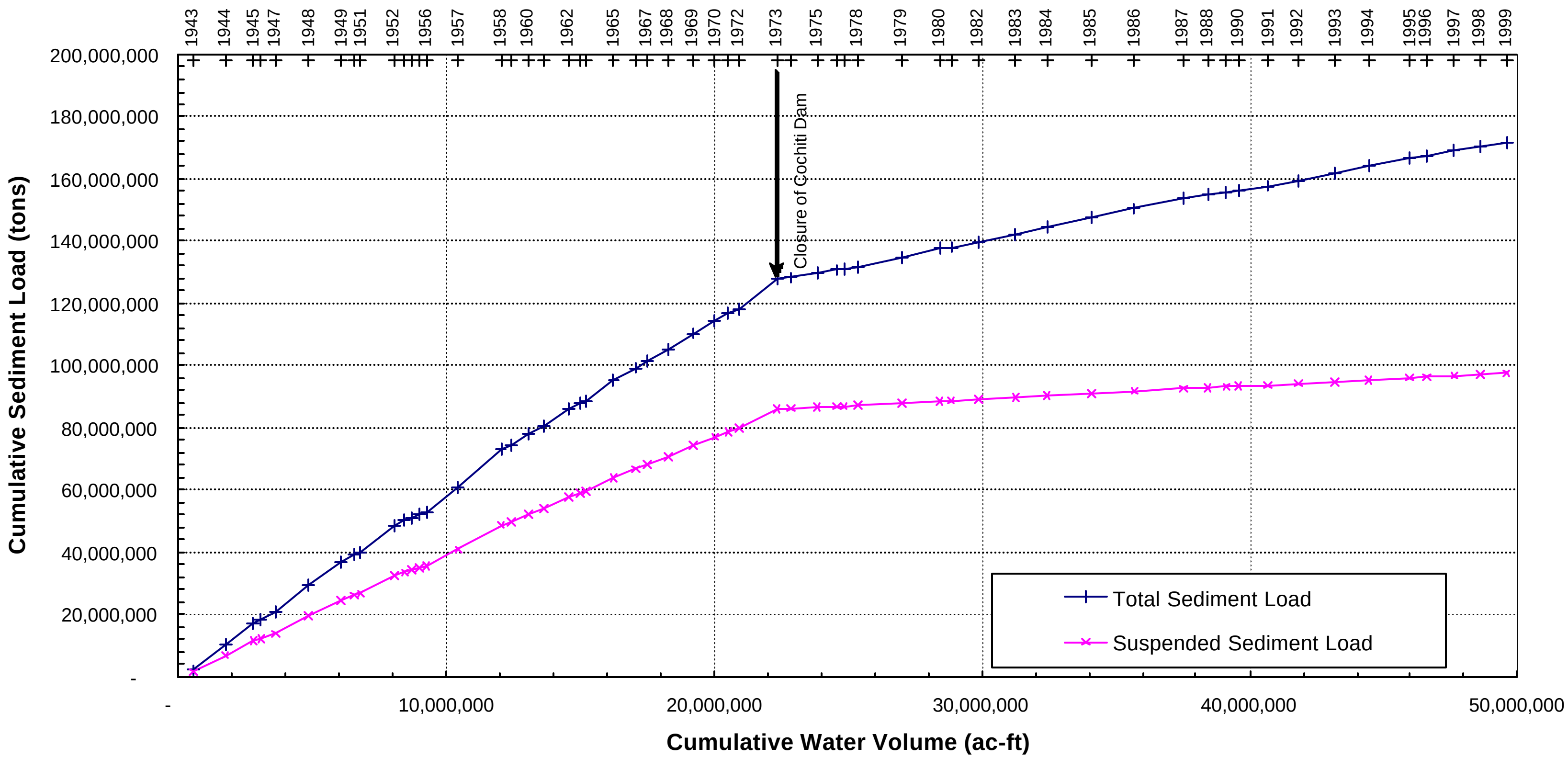


Figure 3.59. Cumulative quantity of total and suspended sediment that passed the Albuquerque gage as a function of cumulative water volume during the period 1943 through 1999.

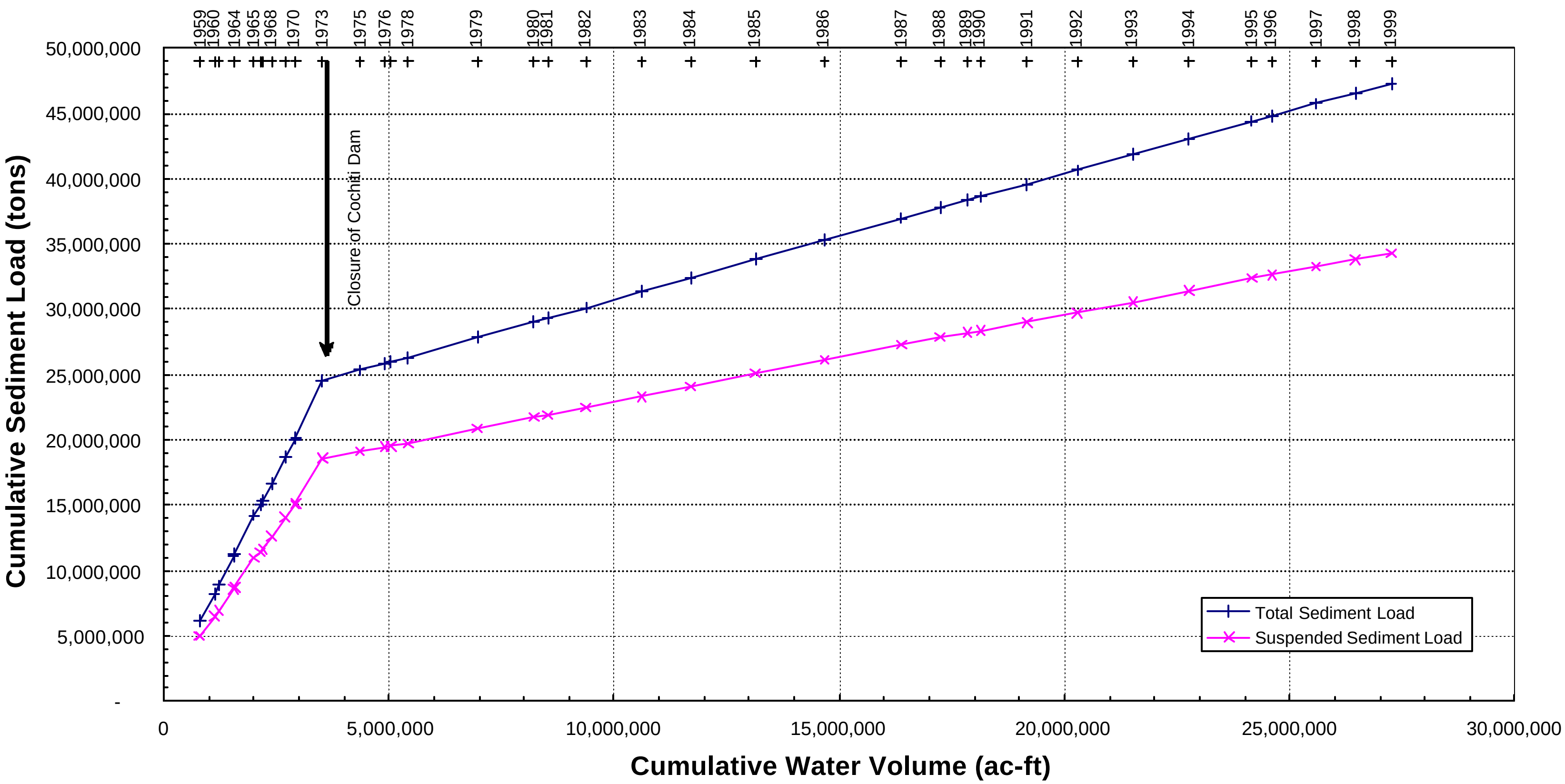


Figure 3.60. Cumulative quantity of total and suspended sediment that passed the Bernardo gage as a function of cumulative water volume during the period 1959 through 1999.

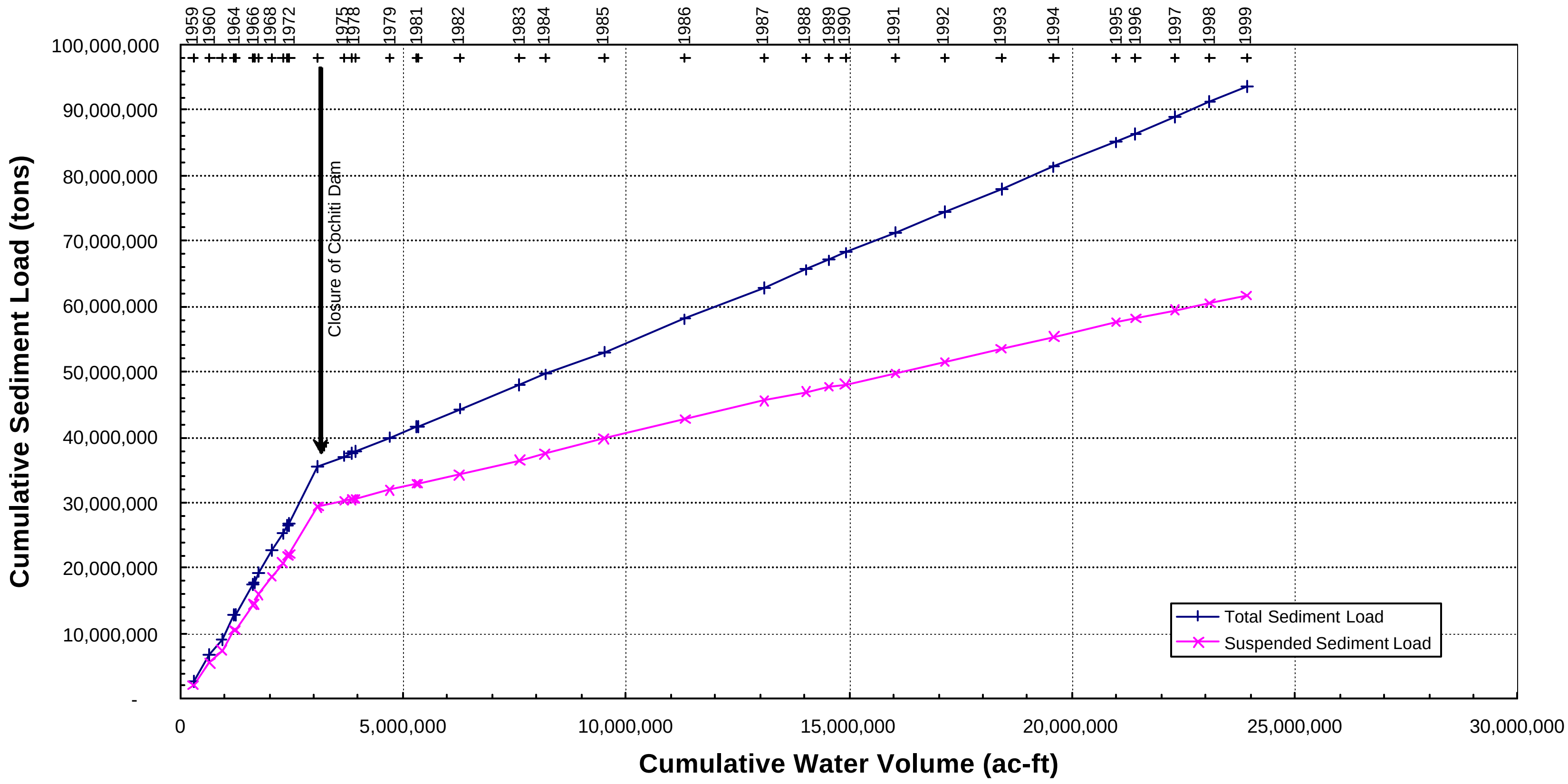


Figure 3.61. Cumulative quantity of total and suspended sediment that passed the San Acacia gage as a function of cumulative water volume during the period 1959 through 1999.

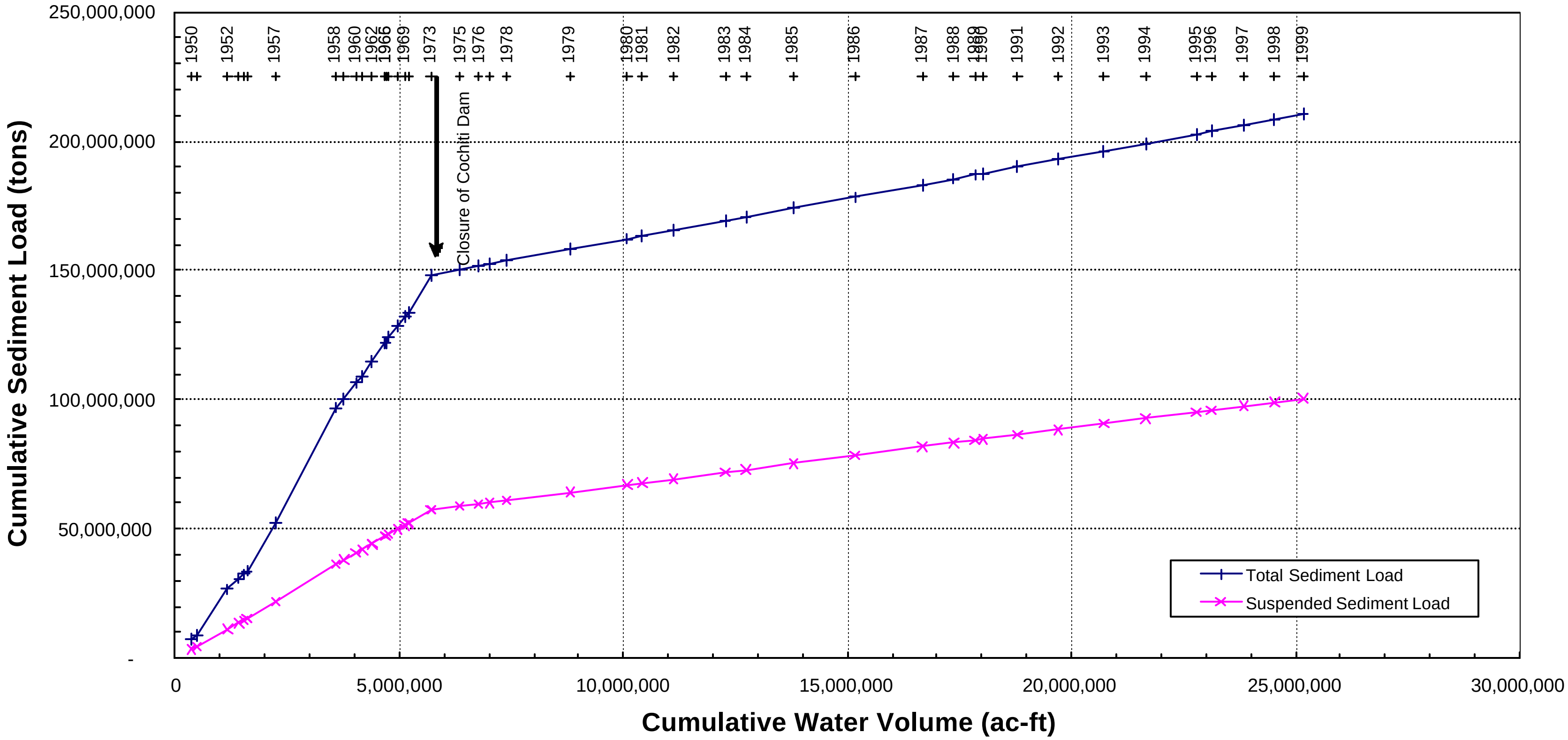


Figure 3.62. Cumulative quantity of total and suspended sediment that passed the San Marcial gage as a function of cumulative water volume during the period 1950 through 1999.

induced factors, including seasonal variations in overland runoff and land use, can also cause this hysteresis behavior.

To evaluate whether or not a seasonal variation in sediment concentration and sediment load occurs in the Rio Grande, the average suspended-sediment concentration and suspended-sediment load was computed for each of the gages on a monthly basis for the post-Cochiti Dam period of record (**Figures 3.63 through 3.68**). At all of the gages, the monthly suspended-sediment loads follow the same general pattern as the monthly runoff volume, with the highest quantity of suspended sediment generally being carried during the months with greatest runoff. The average concentrations, however, do not follow the same pattern at all of the gages. At Otowi (Figure 3.68), for example, a period of elevated suspended-sediment concentrations occurs in April and May during the snowmelt runoff period, and then a second period of elevated concentrations occurs in late summer (August and September). At the Cochiti gage (Figure 3.64), the monthly concentration pattern generally follows the runoff pattern. At the four downstream gages that were considered in the analysis, Albuquerque (Figure 3.65), Bernardo (Figure 3.66), San Acacia (Figure 3.67), and San Marcial (Figure 3.68), the highest monthly concentrations occur in August. This most likely occurs because tributary inflows downstream from Cochiti Dam resulting from summer thunderstorms deliver relatively large quantities of suspended sediment to the river.

Effective Discharge

The concept of effective discharge as initially advanced by Wolman and Miller (1960) related the frequency and magnitude of various discharges to their ability to do "geomorphic work" by transporting sediment. They concluded that events of moderate magnitude and frequency transported the most sediment over the long-term. Andrews (1980) defined the effective discharge as " *the increment of discharge that transports the largest fraction of the annual sediment load over a period of years."*

Alluvial rivers adjust their shape in response to flows that transport sediment, and numerous authors have attempted to relate the effective discharge to the concepts of dominant discharge, channel forming discharge and bankfull discharge (Benson and Thomas, 1966; Pickup, 1976; Pickup and Werner, 1976; Andrews, 1980, 1986; Nolan et al., 1987; Andrews and Nankervis, 1985). However, Baker (1977) and Wolman and Gerson (1978) concluded that in more arid environments less frequent, higher magnitude flood events were the most important with respect to sediment transport. However, the interrelationships of these concepts are not universally accepted (Biedenharn et al., 2000). Regardless of the scientific debate on the interrelationships, quantification of the range of flows that transport the most sediment provides useful information with which to assess the current state of adjustment of the channel, and to evaluate the potential effects of increased discharge and sediment delivery to the channel. Although various investigators have used only the suspended-sediment load and the total sediment load to compute the effective discharge, the bed-material load should generally be used when evaluating the linkage between sediment loads and channel size because it is the bed-material load that has the most influence on the form of the channel (Schumm, 1963; Biedenharn et al., 2000).

The effective discharge was computed by dividing the range of flows during the period of record into a number of arithmetic classes, and then computing the total quantity of sediment transported by the flows within each class (Biedenharn et al., 2000). Effective discharge computations were made based on the suspended-sediment loads that were reported by the

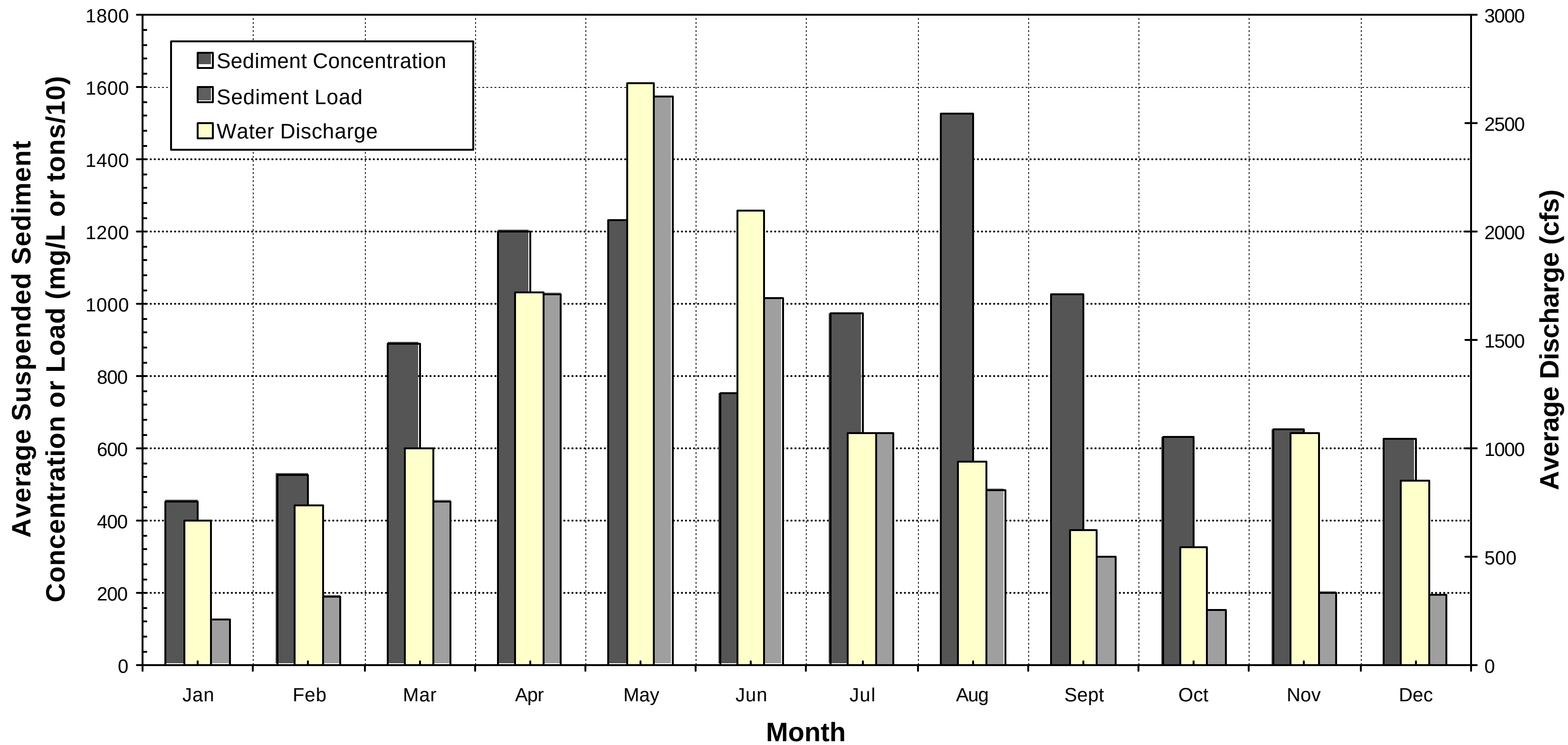


Figure 3.63. Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the period 1974 to 1999 at the Otowi gage.

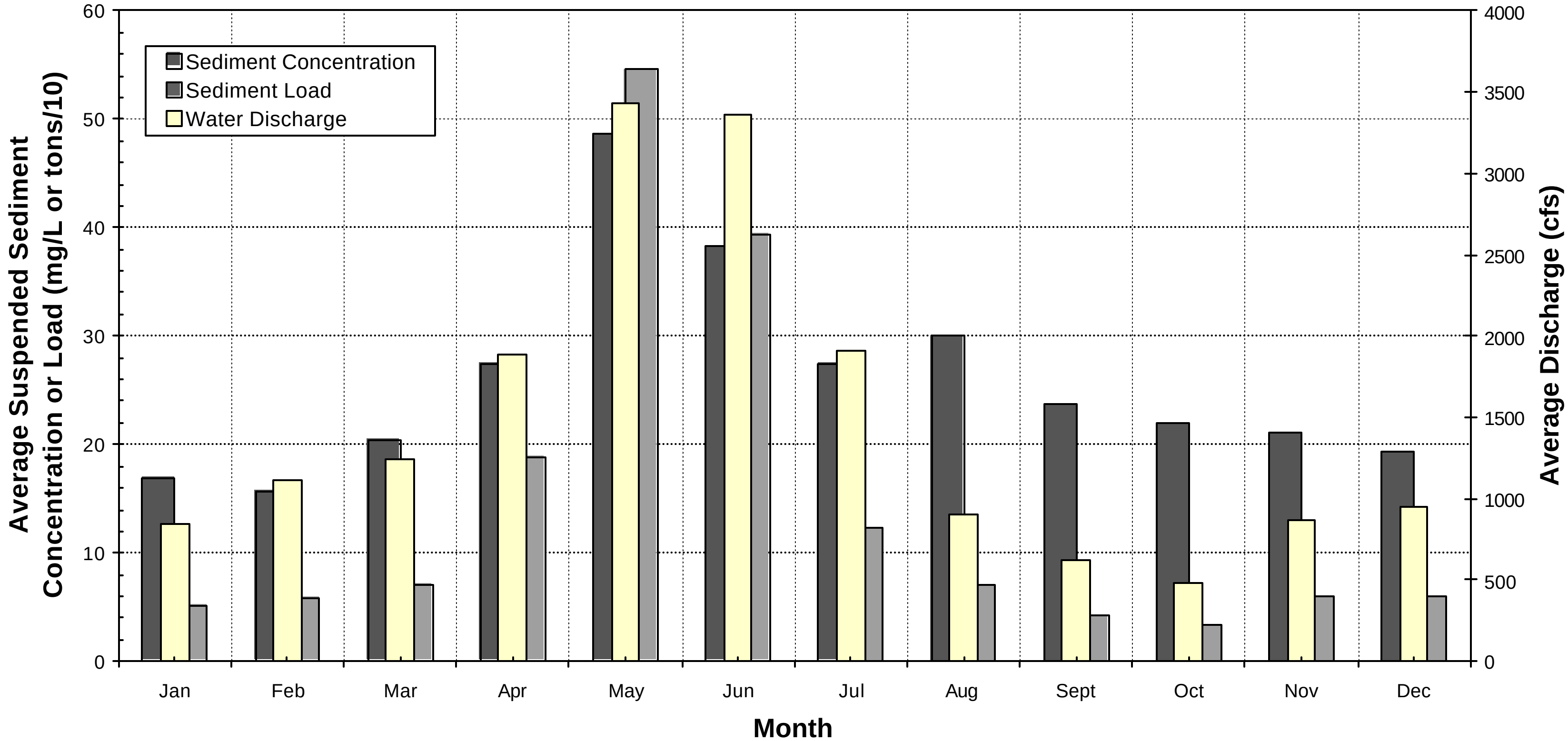


Figure 3.64 Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the post-Cochiti Dam period (1974-1999) at the Cochiti gage.

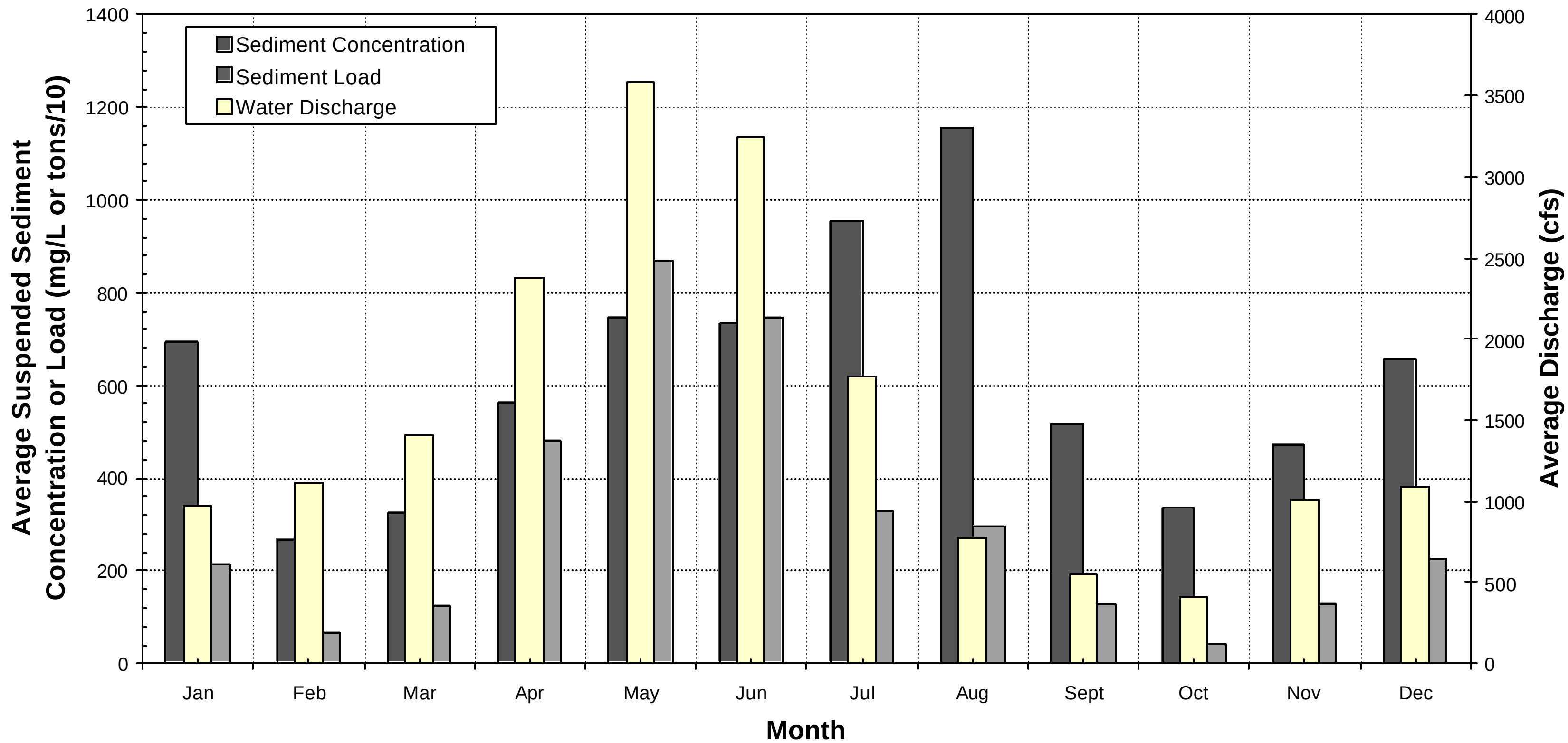


Figure 3.65. Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the post-Cochiti Dam period (1974-1999) at the Albuquerque gage.

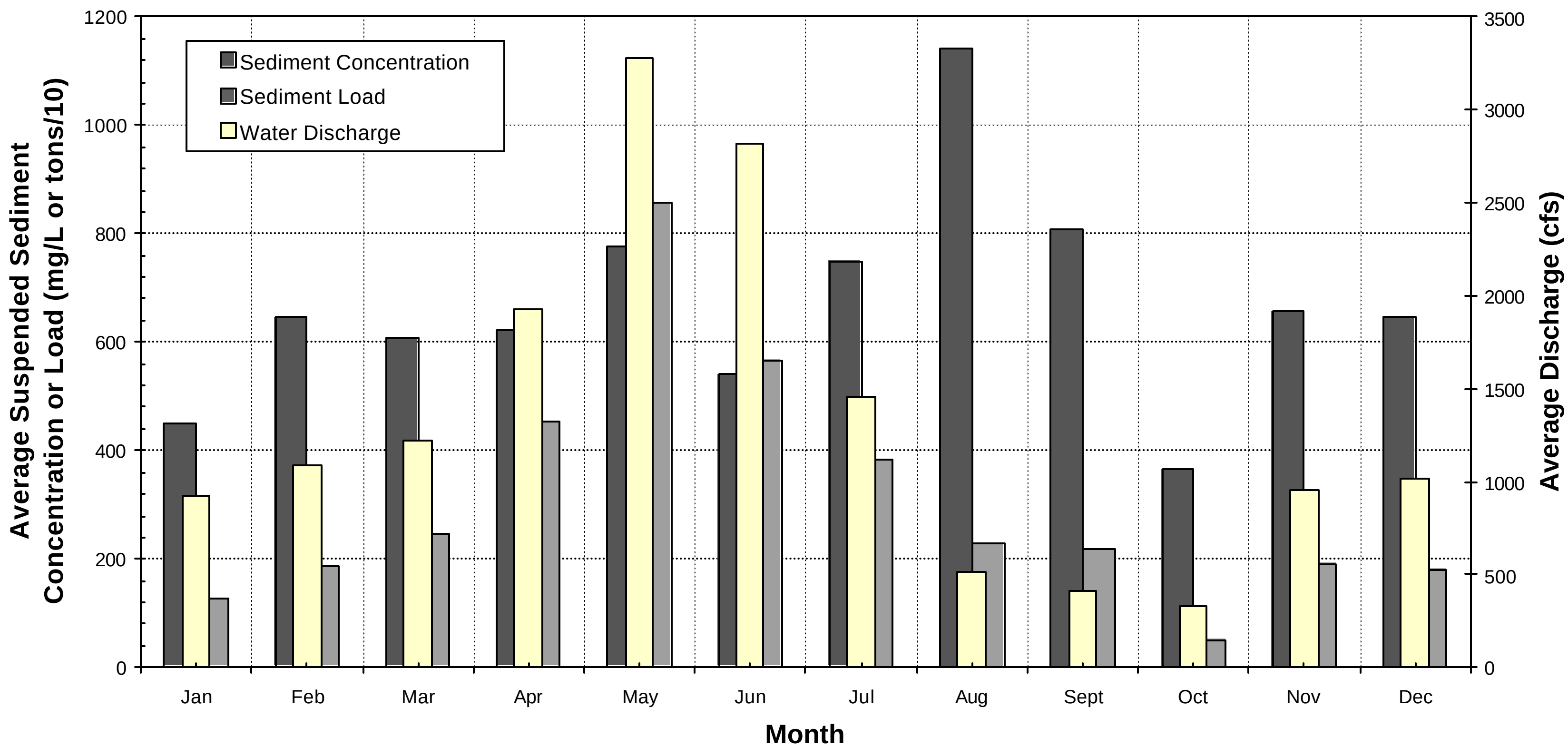


Figure 3.66. Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the post-Cochiti Dam period (1974-1999) at the Bernardo gage.

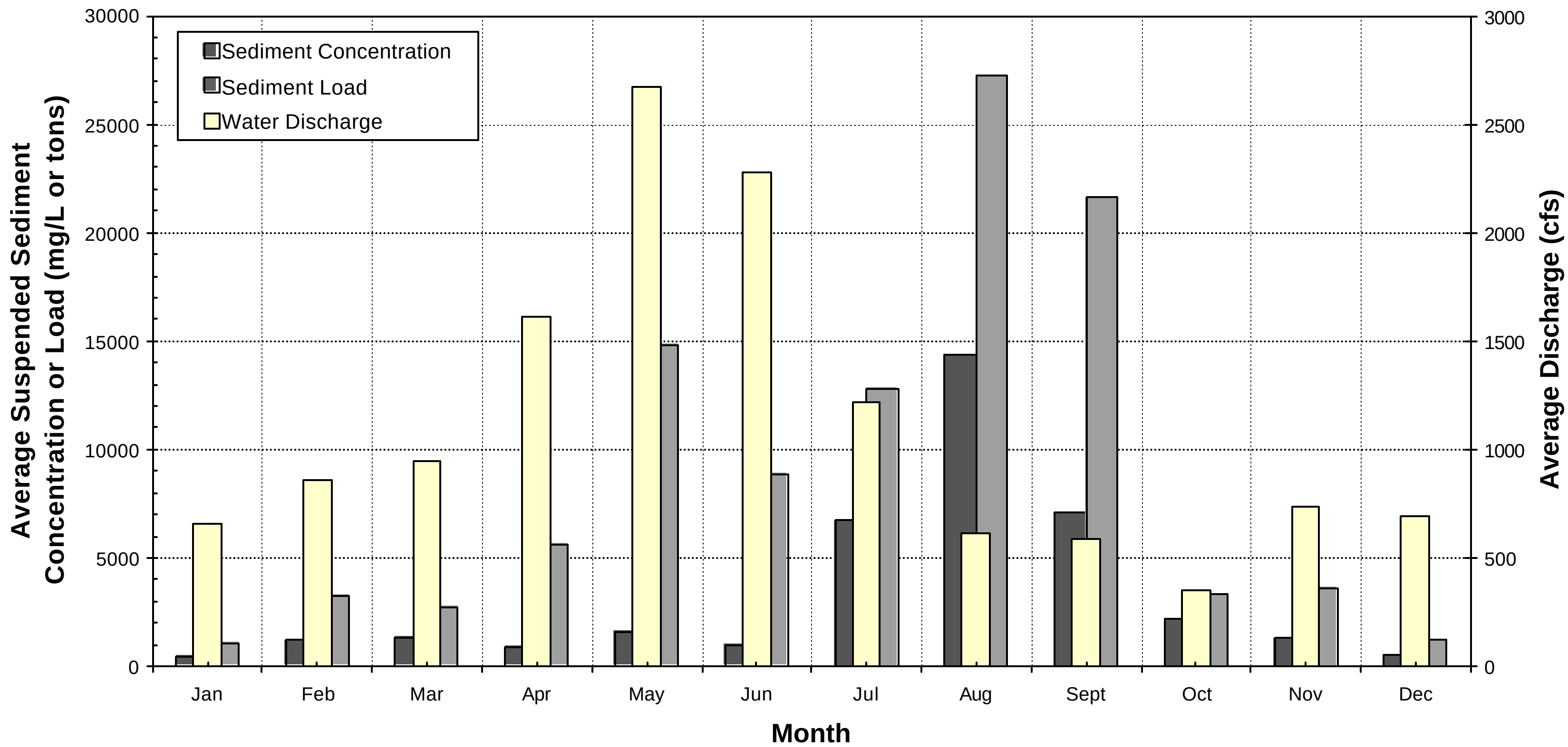


Figure 3.67. Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the post-Cochiti Dam period (1974-1999) at the San Acacia gage.

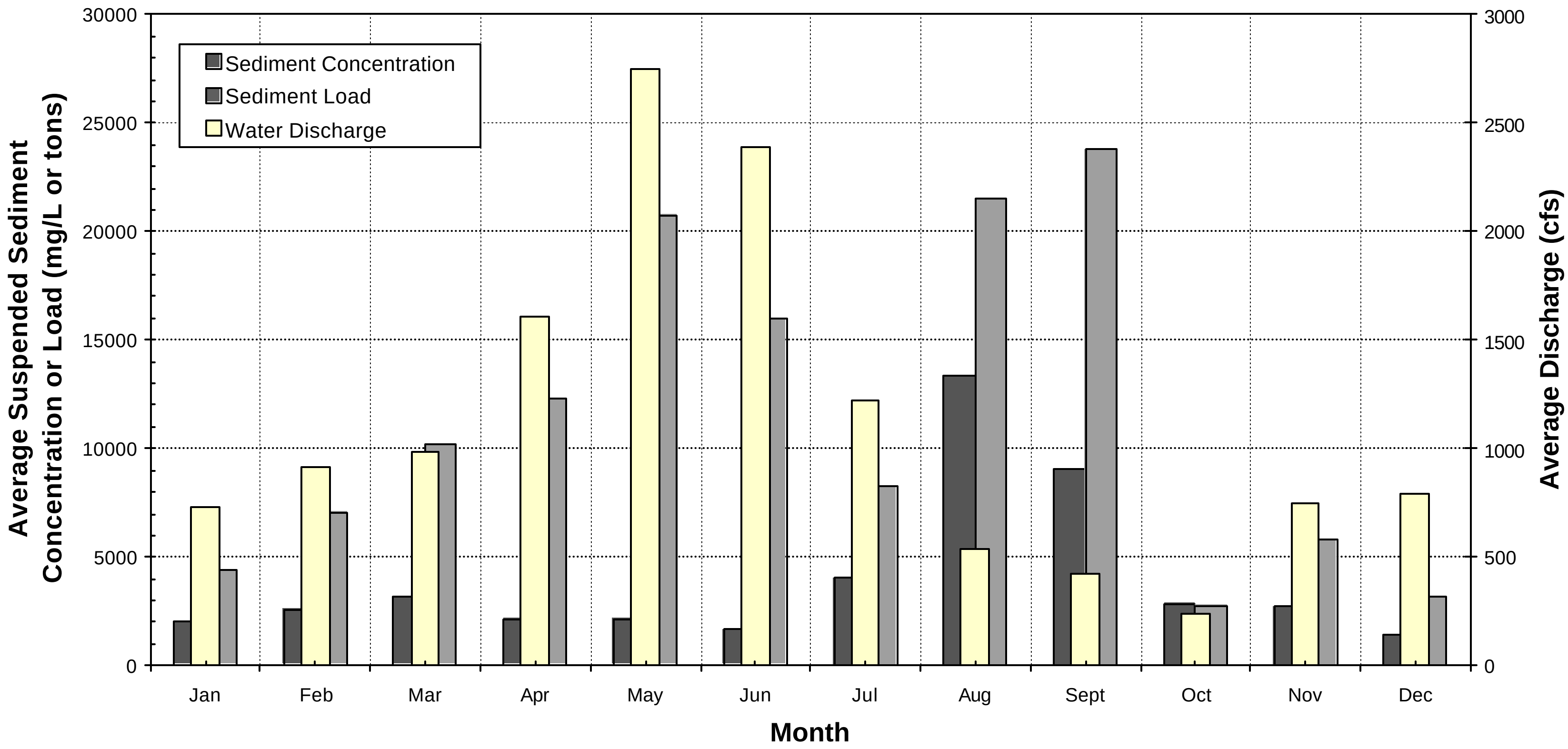


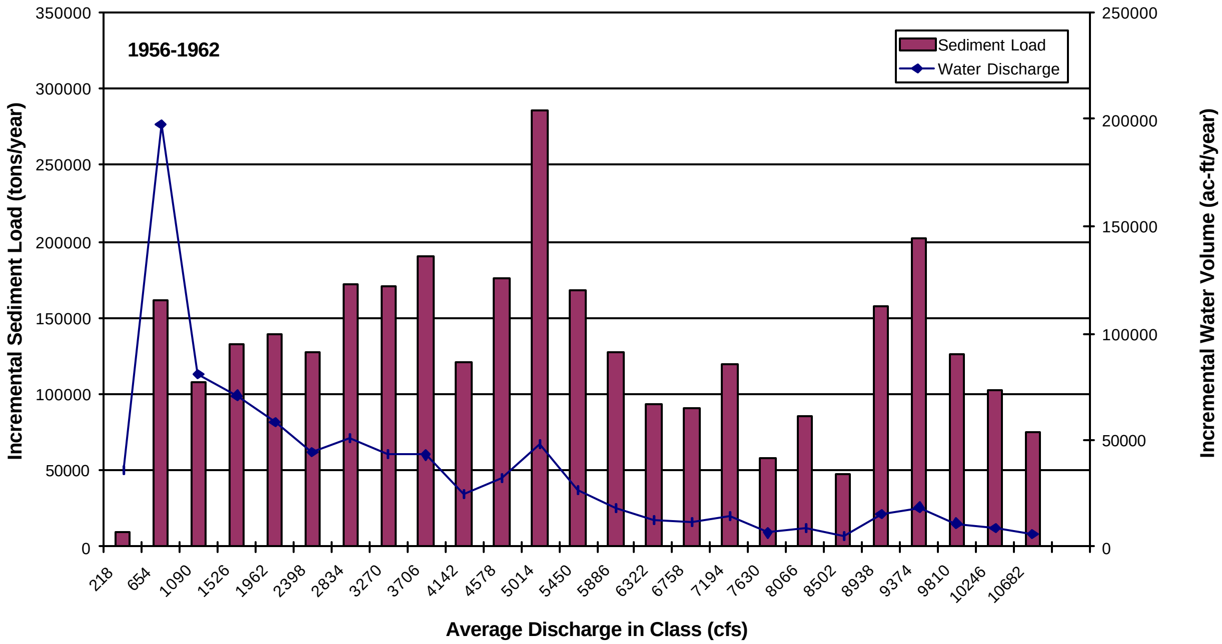
Figure 3.68. Average monthly suspended-sediment concentration, suspended-sediment load, and runoff volume for the post-Cochiti Dam period (1974-1999) at the San Marcial gage.

USGS for the pre- and post-Abiquiu Dam periods at the Otowi gage (**Figure 3.69**), and the computations were made using the bed-material rating curves for the gages downstream from Cochiti Dam (**Figures 3.70 through 3.76**). (Suspended-sediment loads were used for the Otowi gage because bed-material load data were not available.) The results of these computations are summarized in **Table 3.8**. For comparison purposes, the effective discharges were also computed using the reported suspended-sediment loads, where available, and these results are summarized in **Table 3.9**.

At the Otowi gage, the effective discharge for the pre-Abiquiu period was 5,010 cfs, and it decreased to about 1,200 cfs during the post-Abiquiu period (Figure 3.69). The pre-Abiquiu effective discharge corresponds to an approximately 1.25-year flood peak based on the pre-Abiquiu flood-frequency curve, and the post-Abiquiu effective discharge was exceeded by all of the annual peaks in the post-Abiquiu period. Based on the post-Abiquiu mean daily flow-duration curve, the post-Abiquiu effective discharge is equaled or exceeded approximately 10 percent of the time. At the Cochiti gage, the pre-Cochiti Dam effective discharge using the bed material rating curve was about 4,900 cfs, but was only 1,340 cfs using the suspended-sediment load. The effective discharge based on bed-material load corresponds to an approximately 1.5-year flood peak based on the pre-Cochiti flood-frequency curve (Figure 3.11), and the annual peak discharge exceeded the suspended sediment result every year in the record. The pre-Cochiti Dam effective discharge results based on the bed-material load rating curves for the other gages downstream from Cochiti Dam varied from about 1,280 cfs at San Felipe to 2,340 cfs at Bernardo, and then decreased back to 1,310 cfs at San Marcial. The period of record at the Albuquerque gage was too short to make an effective discharge calculation for the pre-Cochiti Dam period. Effective discharges based on the suspended-sediment loads were the same as those obtained using the bed-material rating curves at San Acacia and San Marcial, and were generally lower at the other upstream gages. The effective discharges based on both the suspended- and bed-material loads were equaled or exceeded nearly every year in the annual peak flow record. In evaluating these results, it is important to recognize that the periods of record for the pre-Cochiti Dam sediment data were relatively short at most of the gages, and thus, the error bands on the results are likely very large.

Table 3.8 shows that the effective discharges (based on the bed-material load) for the post-Cochiti period at all of the gages where sufficient data were available to make a comparison with the pre-dam period were lower in the post-dam period. The effective discharges were equaled or exceeded about 40 percent of the time on the post-Cochiti mean daily flow-duration curves at the San Felipe (Figure 3.24), Bernardo (Figure 3.26), San Acacia (Figure 3.27), and San Marcial (Figure 3.28) gages. However, at the Albuquerque gage (Figure 3.25), the effective discharge, based on the bed-material load is only equaled or exceeded about 4 percent of the time on the post-Cochiti mean daily flow-duration curve and is very close to the bankfull discharge. This is probably due to the relatively narrow channel that was constructed through the Albuquerque reach. At all of the gages except the Albuquerque gage, the effective discharges computed using the suspended-sediment loads were very similar to those computed using the bed-material loads (Tables 3.8 and 3.9). Interestingly, the exceedence value (50 percent) for the effective discharge based on the suspended-sediment load is very similar to those computed for the other gages (about 40 percent).

The computed effective discharges at the various gages along the study reach for the post-dam period represent relatively low flows that do not correspond to the bankfull or channel forming discharge that would indicate that there is an equilibrium between the discharge regime, sediment load and channel geometry. In a typical equilibrium channel that is bounded by a floodplain, the peak of the effective discharge curve (or histogram) generally occurs near the bankfull discharge because the in-channel energy, and thus, sediment-transport capacity,



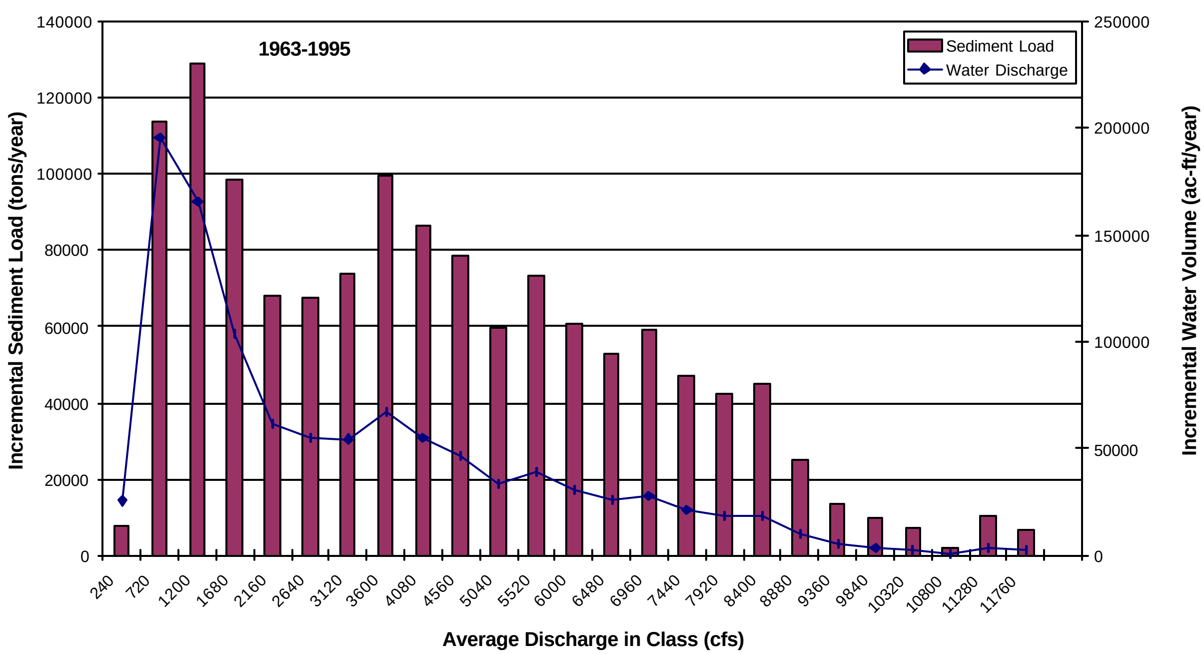


Figure 3.69. Histograms of incremental suspended-sediment load by discharge class for the pre- and post-Abiquiu periods at the Otowi gage. Also shown is the incremental water volume within each discharge class.

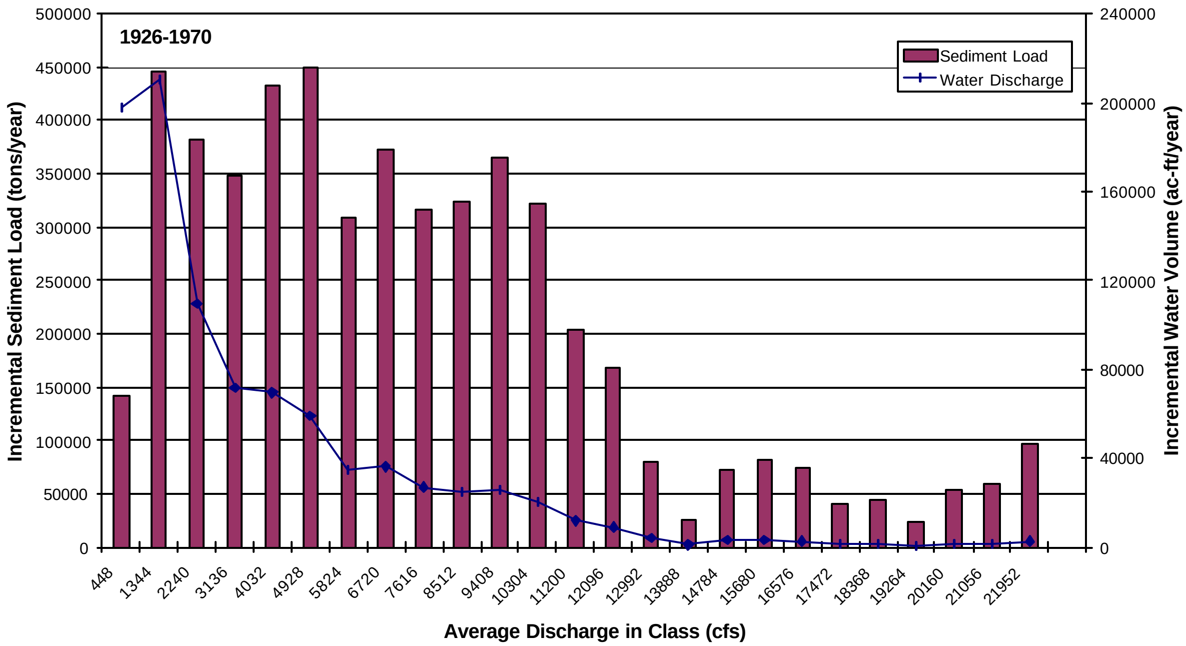
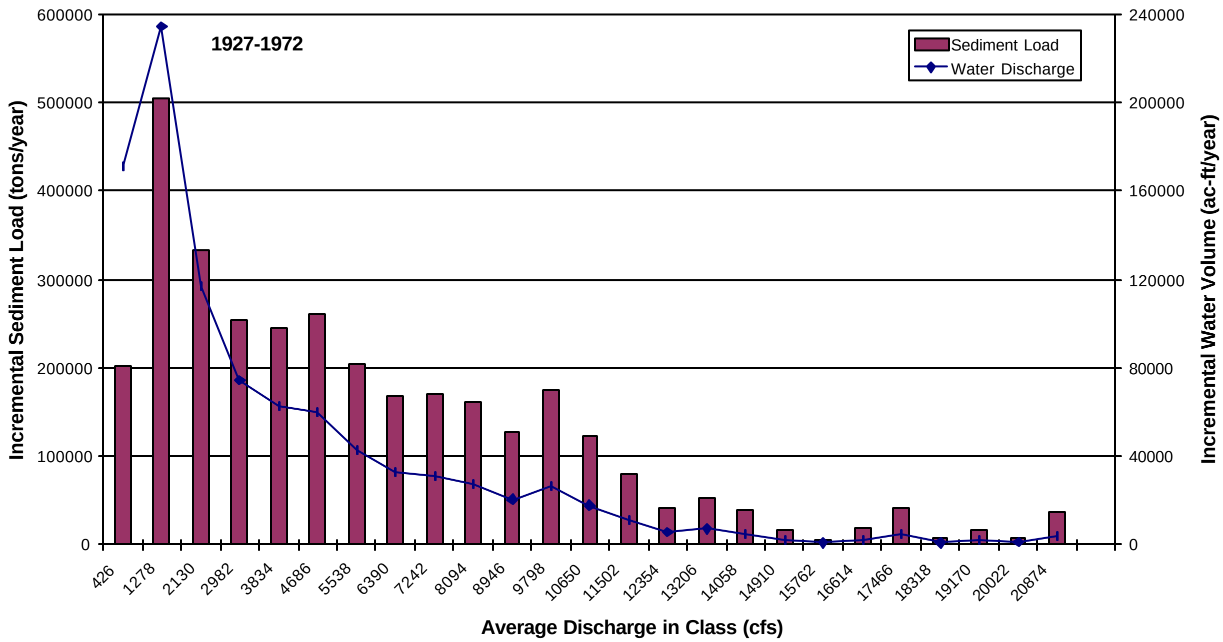


Figure 3.70. Histogram of incremental bed-material load by discharge class for the pre-Cochiti Dam period at the Cochiti gage. Also shown is the incremental water volume within each discharge class.



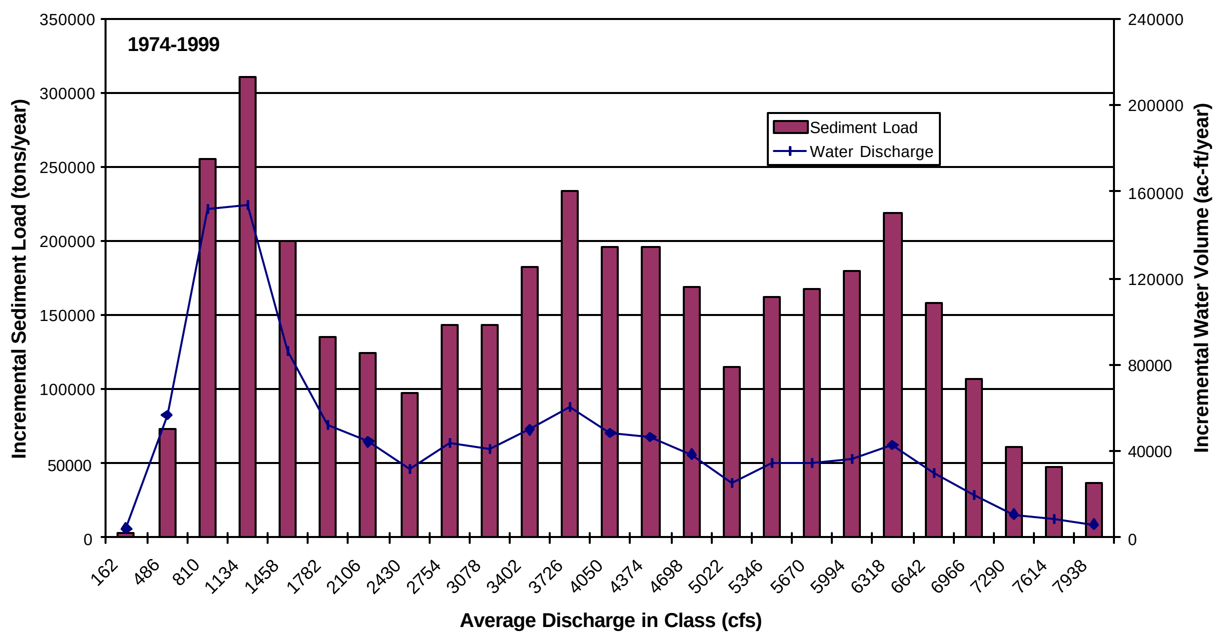


Figure 3.71. Histograms of incremental bed-material load by discharge class for the pre- and post-Cochiti Dam periods at the San Felipe gage. Also shown is the incremental water volume within each discharge class.

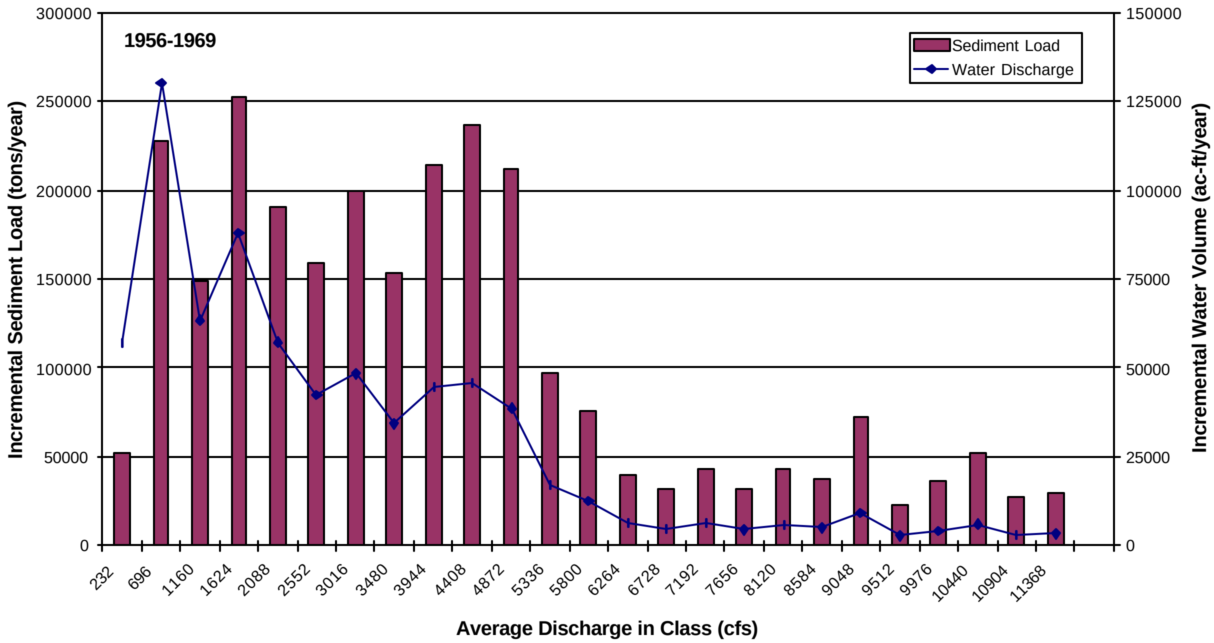


Figure 3.72. Histogram of incremental bed-material load by discharge class for the pre-Cochiti Dam period at the Bernalillo gage. Also shown is the incremental water volume within each discharge class.

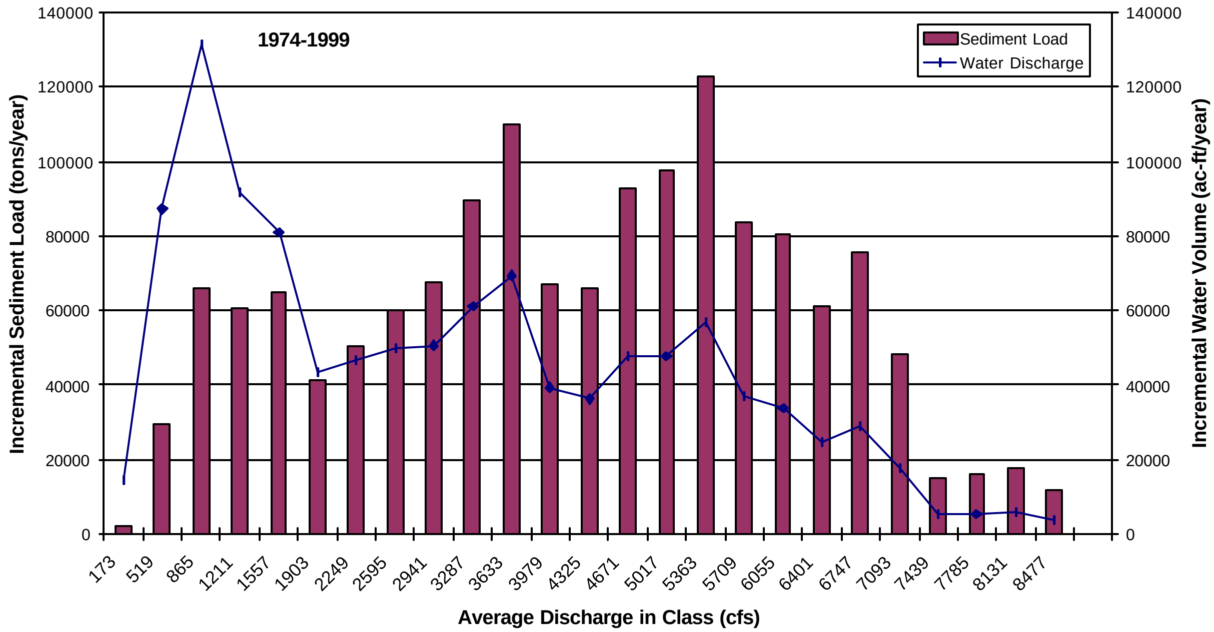
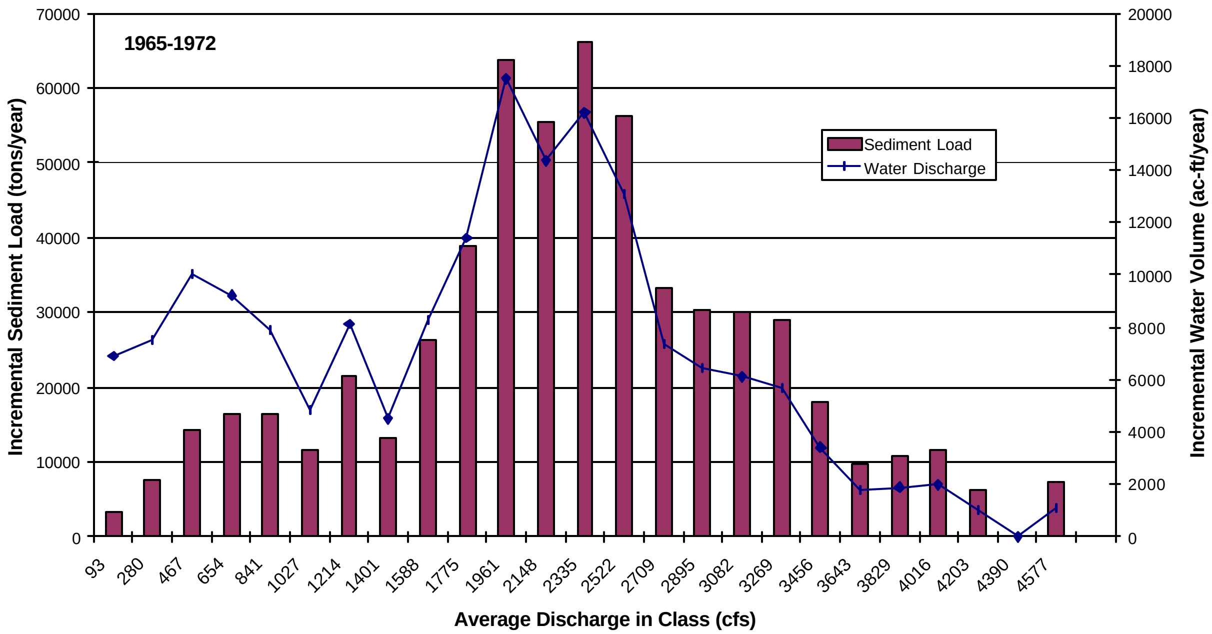


Figure 3.73. Histogram of incremental bed-material load by discharge class for the post-Cochiti Dam period at the Albuquerque gage. Also shown is the incremental water volume within each discharge class.



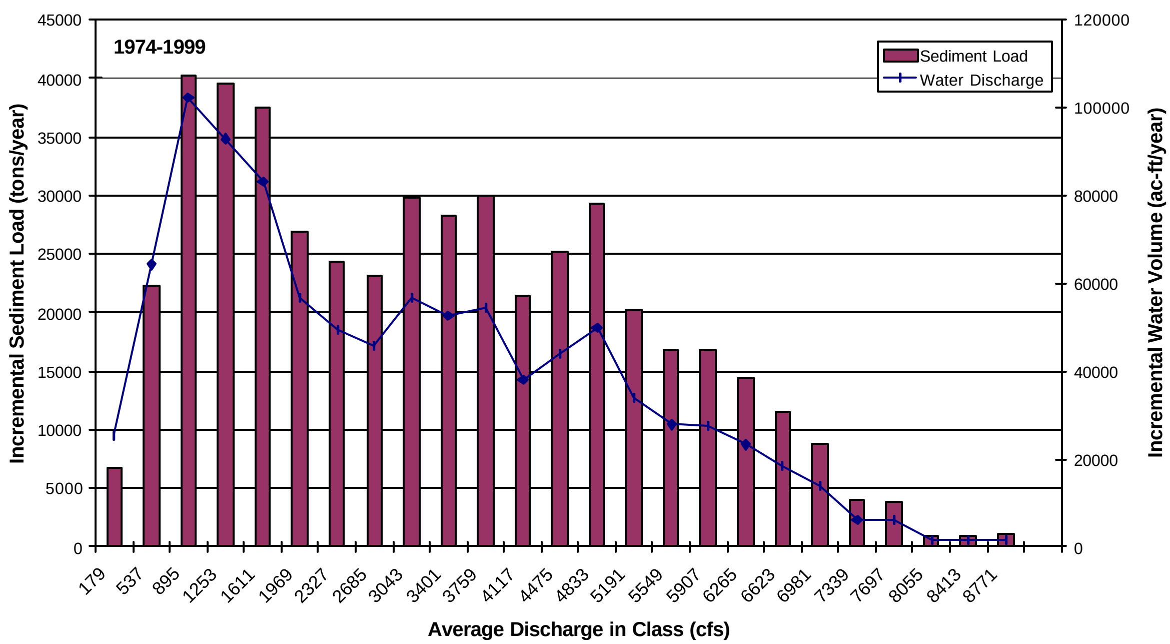
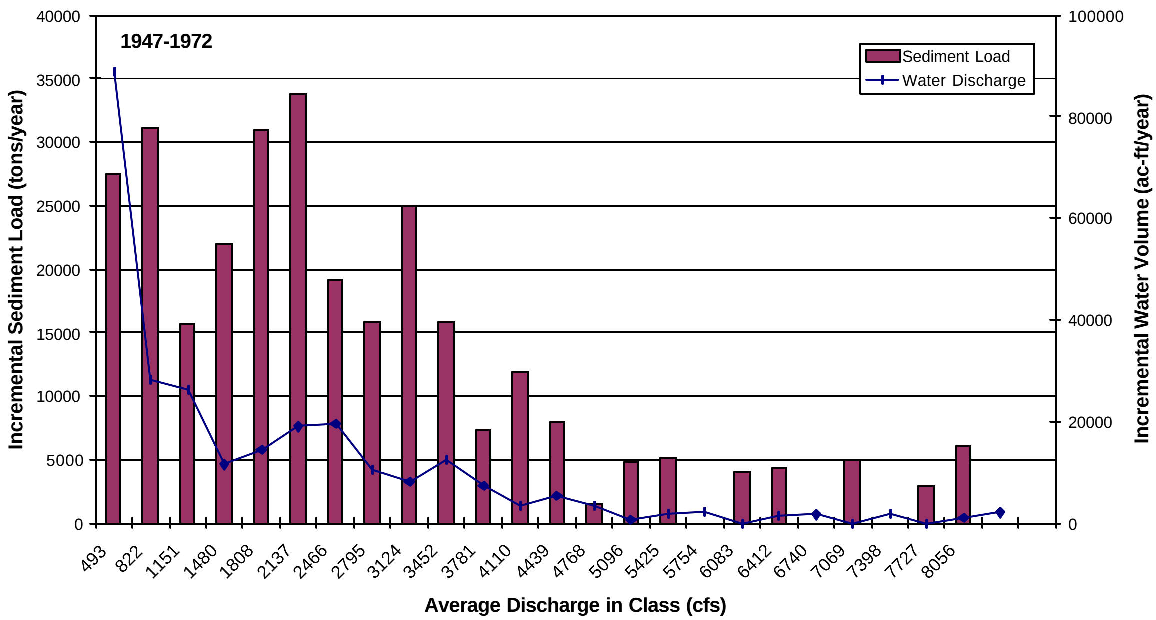


Figure 3.74. Histograms of incremental bed-material load by discharge class for the pre- and post-Cochiti Dam periods at the Bernardo gage. Also shown is the incremental water volume within each discharge class.



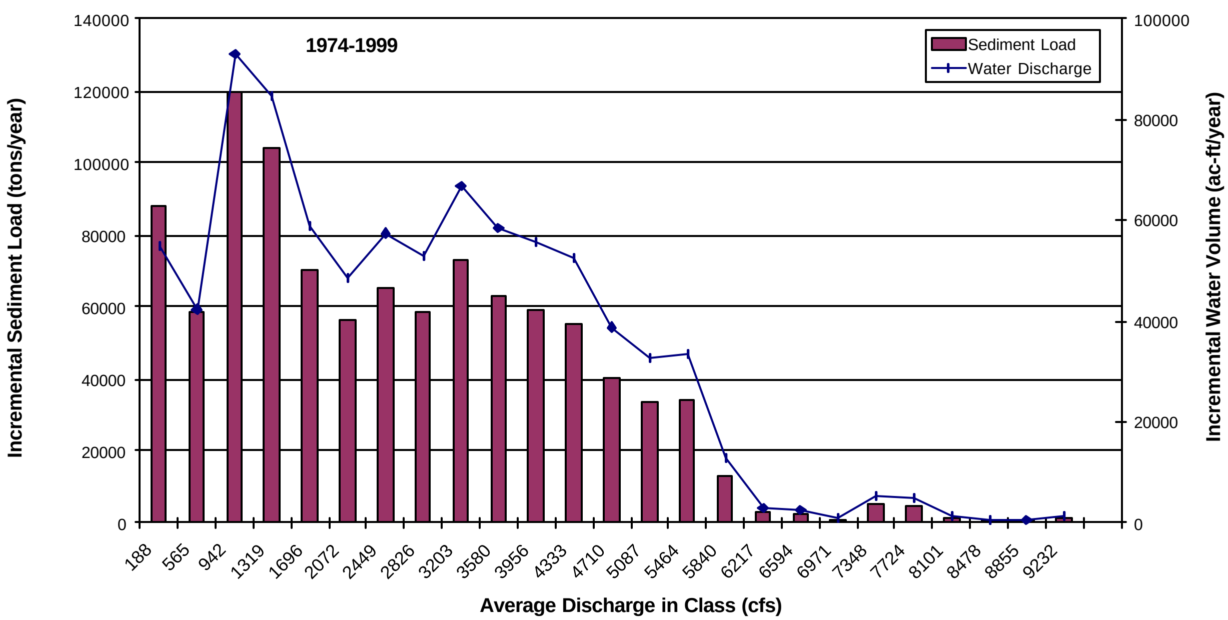


Figure 3.75. Histograms of incremental bed-material load by discharge class for the pre- and post-Cochiti Dam periods at the San Acacia gage. Also shown is the incremental water volume within each discharge class.

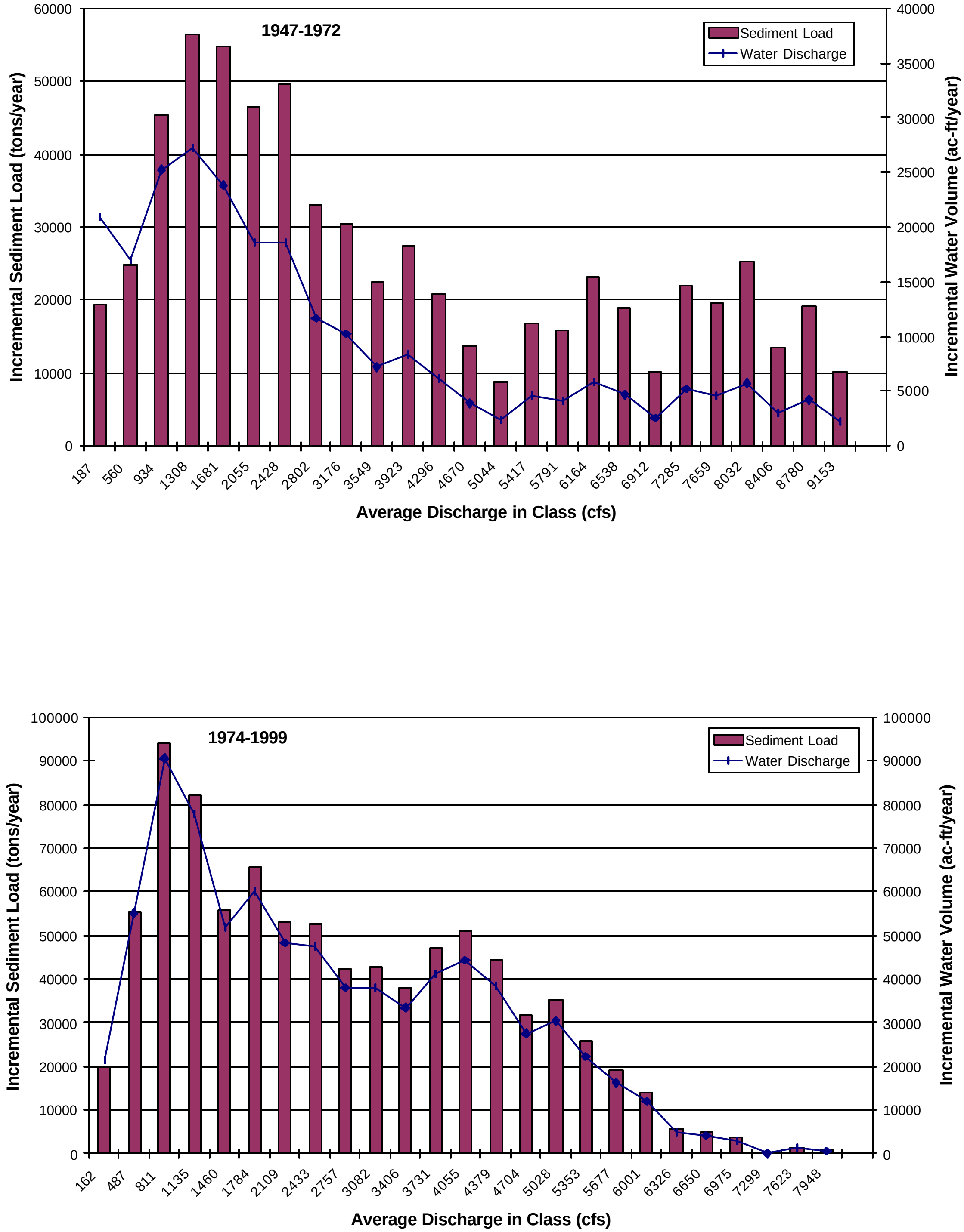


Figure 3.76. Histograms of incremental bed-material load by discharge class for the pre- and post-Cochiti Dam periods at the San Marcial gage. Also shown is the incremental water volume within each discharge class.

Table 3.8. Summary of calculated effective discharges based on bed-material rating curves.

Gage Name	Station ID	Effective Discharge (cfs)	
		Pre-Dam[1]	Post-Dam[1]
Rio Grande at Otowi Bridge, NM	08313000	5,010	1,200
Rio Grande at Cochiti, NM	08314500	4,930	
Rio Grande at San Felipe, NM	08319000	1,280	1,130
Rio Grande at Bernalillo, NM	08329500	1,620	
Rio Grande at Albuquerque, NM	08330000		5,360
Rio Grande Floodway at Bernardo, NM	08332010	2,340	900
Rio Grande Floodway at San Acacia, NM	08354500 08354900	2,140	940
Rio Grande Floodway at San Marcial, NM	08358400 08358500	1,310	810

[1]Values at Otowi represent pre- and post-Abiquiu Dam periods (pre-1963 and post-1963; all other gages based on pre- and post-Cochiti Dam periods (pre-1973 and post-1973).

Table 3.9. Summary of estimated effective discharges based on suspended-sediment rating curves.

Gage Name	Station ID	Effective Discharge (cfs)	
		Pre-Dam[1]	Post-Dam[1]
Rio Grande at Otowi Bridge, NM	08313000	5,010	1,200
Rio Grande at Cochiti, NM	08314500	1,340	
Rio Grande at San Felipe, NM	08319000	490	1,130 [2]
Rio Grande at Bernalillo, NM	08329500	700	
Rio Grande at Albuquerque, NM	08330000		870
Rio Grande Floodway at Bernardo, NM	08332010	1,960	900 [2]
Rio Grande Floodway at San Acacia, NM	08354500 08354900	2,140 [2]	940 [2]
Rio Grande Floodway at San Marcial, NM	08358400 08358500	1,310 [2]	810 [2]

[1]Values at Otowi represent pre- and post-Abiquiu Dam periods (pre-1963 and post-1963); all other gages based on pre- and post-Cochiti Dam periods (pre-1973 and post-1973).

[2]Same result as bed material.

increases relatively rapidly up to the bankfull stage. At stages above bankfull, flow spreads onto the floodplain and incremental increases in discharge results in very small to negligible increases in in-channel energy that is available to transport sediment. This is clearly not the case along the Middle Rio Grande, and the computed effective discharges are simply an artifact of the current flow distribution and sediment sizes at the individual gages.

3.4. Sediment Sources

Rittenhouse (1944) and Happ (1948) concluded on the basis of the mineralogy of the sand-size fraction of the bed material along the Middle Rio Grande and the assumption that the tributaries contributed sediment in proportion to their drainage areas, that the supply of sediment from various sources could be quantified (**Table 3.10**). If the same percentages are applied to the post-dam period then it is apparent that construction of the Jemez Reservoir (1953), Galisteo Reservoir (1970) and Cochiti Reservoir (1973) eliminated on the order of 35 percent of the sediment load from the reach of the Rio Grande downstream of the Jemez River confluence. With the exception of a few larger tributaries in Reaches 1 and 2, the bulk of the tributaries are located in Reaches 5, 6 and 7 (Figure 1.1). The estimates in Table 3.10, therefore, indicate that historically, about 65 percent of the sediment supply to the Middle Rio Grande occurred downstream of the confluence with the Rio Puerco. Because of the presence of the upstream dams, as well as the channelization and bank stabilization that have occurred along the entire river, almost 100 percent of the sediment supply now comes from the minor tributaries and the Rio Puerco and Rio Salado, and this is primarily supplied to the river in Reaches 5, 6 and 7. The reduction in the supply of sediment from the Rio Puerco as the incised channel has evolved to a condition that promotes storage of sediment (Schumm et al., 1984; Gellis et al., 1991) means that the supply, even to the lower reaches of the river, has been reduced over time (USBR, 1992).

Table 3.10. Proportion of sand-sized sediment supplied to the Middle Rio Grande from various sources (Rittenhouse, 1944; Happ, 1948).

Source Of Sediment	Proportion of Total Supply (Percent)
Rio Grande above Cochiti	19
Santa Fe River	1
Galisteo Creek	3
Jemez River	12
Rio Puerco	35
Rio Salado	13
Minor Tributaries	17

Some measure of the amount of sediment that was supplied by the tributaries can be ascertained from reservoir sedimentation surveys. Based on resurveys of Jemez Reservoir since the initial closure of the dam in 1953, about 19,800 acre-feet (440 acre-feet/year) have been trapped in the reservoir (COE, 2000). Based on an upstream watershed area of 1,034 mi^2, the average sediment yield would have been about 0.43 acre-feet/mi^2/yr. Based on resurveys of Cochiti Reservoir since the initial closure in 1973, about 27,340 acre-feet (1,100 acre-feet/year) have been trapped in the reservoir (COE, 2002). Based on an upstream watershed area of 11,695 mi^2, the average sediment yield has been about 0.1 acre-feet/mi^2/yr. The reduced unit sediment yield is expected because of the larger size of the watershed (Schumm, 1977). The volume of material trapped in Cochiti Reservoir equates to an annual load of about 2.4 M tons (at 100 lb/cf) which is reasonably close to the estimate of annual bed-material load (2.8M tons) based on the bed-load rating curves at the Cochiti gage before the reservoir was closed. The Jemez Reservoir data suggest that the annual yield was on the order of 968,000 tons.

Because of the very high trap efficiency of Cochiti Dam, the sediment outflow to the Rio Grande is very low (Table 3.7). Available data from the two largest tributaries between Cochiti and Bernalillo, Galisteo Creek, and the Jemez River, both of which have been dammed, indicate that Galisteo Creek still delivers sediment to the Rio Grande, but Jemez River delivers very little. The pre- and post-Galisteo dam suspended-sediment rating curves (**Figure 3.77**) show that the creek still transport high sediment loads at the higher discharges. In contrast, the suspended-sediment rating curve for Jemez River (**Figure 3.78**) shows very low sediment loads even at the higher discharges in the post-dam period. Channel degradation between Cochiti and Bernalillo has been a significant source of sediment to downstream reaches (Leon, 1998).

Between Bernalillo and Albuquerque, the major sources of sediment are Callabacillas and Montoyas Arroyos, and the North Diversion Channel that collects sediment from the east side arroyos and delivers t to the Rio Grande. Previous investigations have indicated that the annual unit bed-material yield from Callabacillas Arroyo is on the order of 1.6 T/acre (MEI, 1996), and from the North Diversion Channel, it is on the order of 0.7 to 2 T/acre (COE, 1995).

Sediment delivery from the tributaries is a significant, but essentially unquantified, part of the sediment budget of the Middle Rio Grande (Bauer, 2000; Leon, 1998; Lagasse, 1980). The following brief discussion of sediment delivery to the Rio Grande by tributaries is based upon study of the 1962, 1972, and 1992 aerial photographs. As is typical of ephemeral stream channels in the Southwest, the tributaries deliver sediment to the river episodically, depending upon storm events. In addition, any one tributary may deliver large amounts of sediment to the river during a period of years, but then the sediment may be deposited on the floodplain or stored in the tributary channel and valley (**Table 3.11**). The reverse may be observed with a channel depositing sediment on the floodplain in 1962 and then developing a channel that reaches the river at a later date. Table 3.11 illustrates the variability of sediment delivery to the Rio Grande in both location and time. It demonstrates the episodic behavior of ephemeral-stream channels that contribute to the Rio Grande.

In summary, tributary streams can significantly impact the Rio Grande. Although the Jemez River and Rio Galisteo have been dammed, the Rio Puerco and Rio Salado have and continue to significantly affect the river. Lagasse (1980, p. 127) stated that in the Cochiti to Isleta reach of the river, sediment delivery from tributary arroyos "*has dominated the response of the mainstream Rio Grande to altered conditions of flow and sediment transport following closure of the Cochiti Dam.*" He further concluded that the effect of tributaries *"is so pronounced that one can predict with some certainty that an arroyo contributing sediments from more than a 60 square-mile area will exercise some control over mainstem channel characteristics"* (Lagasse, 1980, p. 89).

In addition, sediment delivery can be long delayed as it accumulates on the floodplain eventually to be flushed into the river. The episodic nature of tributary discharge also may result in a long period of sediment storage in the tributary channels that is followed by flushing of the stored sediment into the Rio Grande.

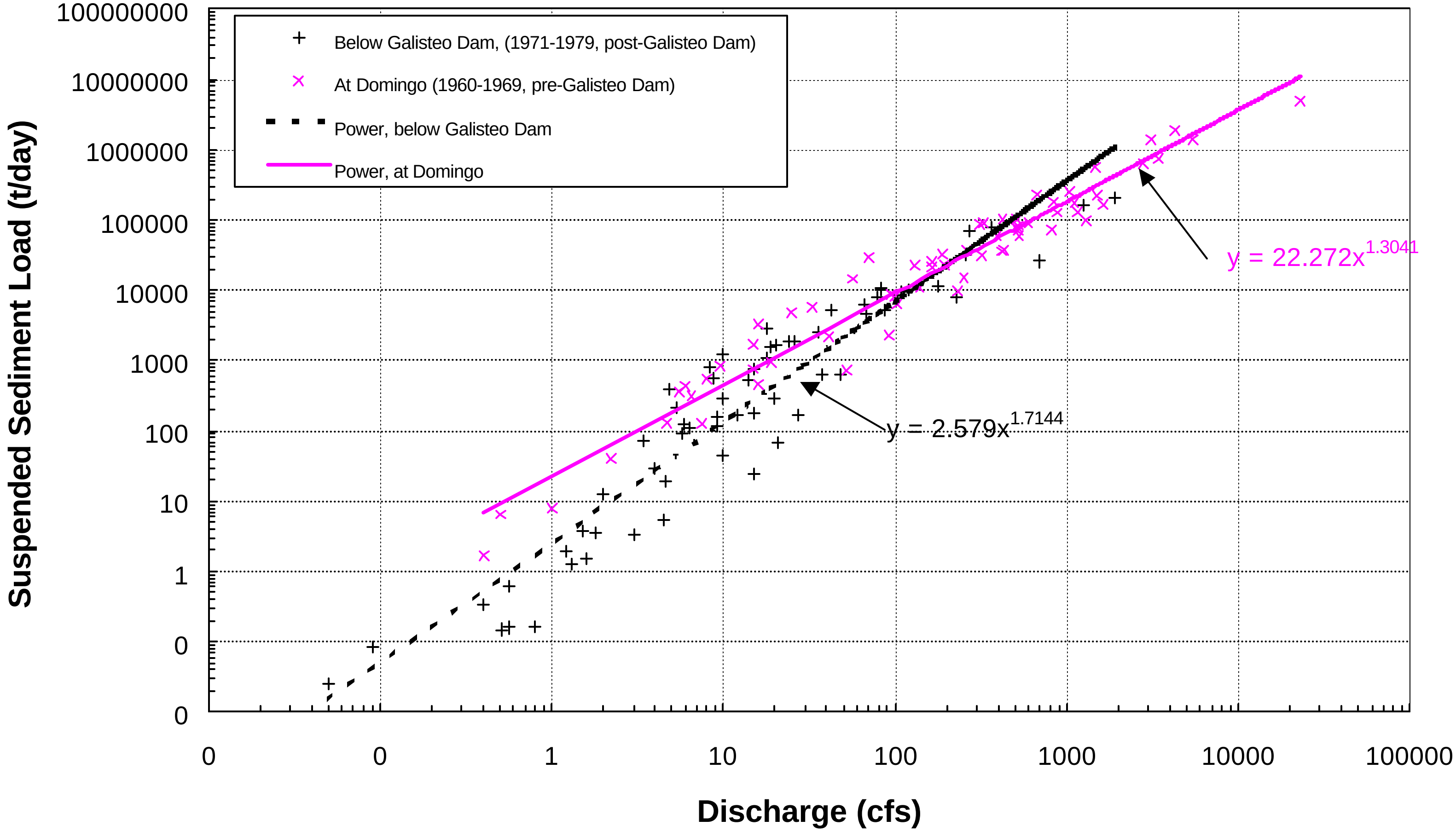


Figure 3.77. Suspended-sediment rating curves for Galisteo Creek at Santo Domingo (1960-1969) and below Galisteo Dam (1971-1979).

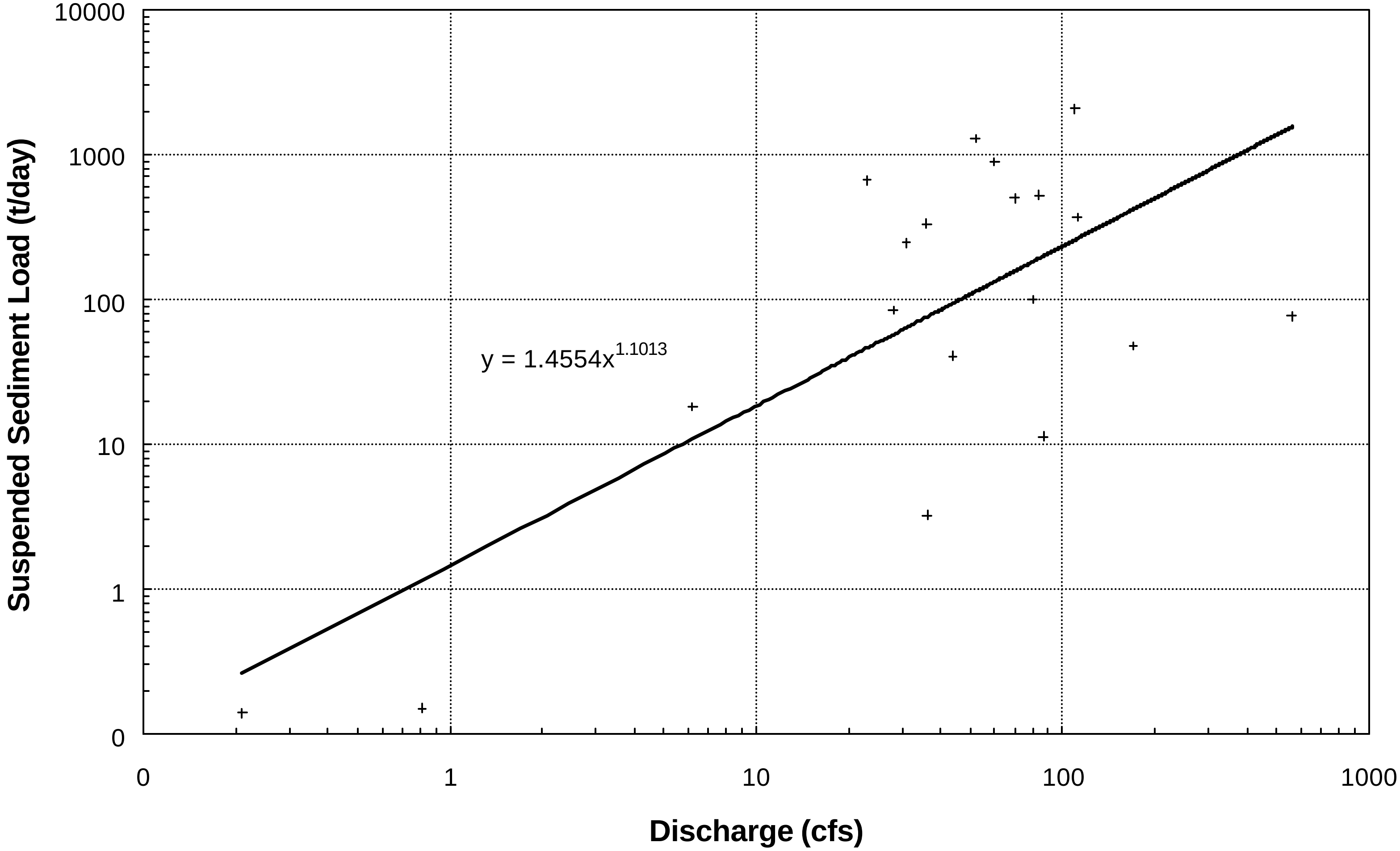


Figure 3.78. Suspended-sediment rating curve for Jemez River downstream of Jemez Reservoir for the period from 1974 to 1996.

Table 3.11. Qualitative evaluation of sediment delivery from tributaries to the Rio Grande from 1962 to 1992 (Yes indicates delivery; No indicates no evidence of delivery).			
Tributary	1962	1972	1992
Santa Fe River	Yes	Yes	No
Peralta Canyon	Yes	Yes	Yes
No Name Arroyo (Sta. 871843)	No	Yes	Yes
Galisteo Creek	Yes	Yes?	No?
Santa Domingo Canyon	No	Yes	Yes
Borrego Canyon	No?	Yes	Yes
Arroyo de la Vega de los Tanos	No?	No?	Yes
Arroyo Tonque	Yes	Yes	Yes
Arroyo Maria Chevez	No	No	Yes
No Name Arroyo (Sta. 799461)	No	No	Yes
Las Huertas Creek	No	No	Yes
Jemez River	Yes	Yes	No?
Arroyo de las Brancas	No?	Yes	Yes
No Name Arroyo (Sta. 731408)	No	No	Yes
AMAFCA North	---	Yes	Yes
Callabacillas Arroyo	Yes	Yes	Yes
AMAFCA South	---	Yes?	Yes
Abo Arroyo	No?	Yes	Yes
Maes Arroyo	Yes	Yes	Yes
Rio Puerco	Yes	Yes	Yes
Salas Arroyo	Yes	Yes	Yes?
Arroyo de los Alamos	Yes	Yes?	No
Canada Ancha	No	No	Yes
Rio Salado	Yes	Yes	Yes
Arroyo Rosa di Castillo	No	Yes	No
Arroyo Alamill	Yes	Yes	Yes
Arroyo de Parida	No	No	Yes
Arroyo de los Pinos	Yes	Yes	No
Arroyo de la Presila	Yes	Yes?	No
No Name Arroyo (Sta. 211798)	No	No	Yes
No Name Arroyo (Sta. 204978)	No	No	Yes
Arroyo de los Canas	Yes	Yes	Yes

The size of the drainage area and slope for many of the Rio Grande tributaries are presented in **Table 3.12**. Typically, larger drainage basins deliver larger quantities of sediment to the mouth. However, comparison of drainage area and the qualitative description of tributary sediment yield to the Rio Grande are highly variable in both time and space. The episodic behavior of the tributaries makes it very difficult to estimate sediment contribution from the tributaries.

3.5. Sediment Movement

Both Leon (1998) and Lagasse (1980) suggest that sediment moves through the Rio Grande in waves. Alternating reaches of aggradation and degradation and changes of the longitudinal profile reflect sediment movement. However, the apparent waves may be sediment deposits that are remobilized rather than waves of sand in continuous movement. In any case, gradient and channel dimensions must change through time.

Table 3.12. Drainage Basin areas and slopes for the larger arroyos draining to the Middle Rio Grande.		
Name	Area (mi^2)	Slope (%)
Peralta Canyon	47.9	19.4
Galisteo Creek	646.7	4.5
Canon Santo Domingo	28.5	6.2
Borrego Canyon	86.7	9.6
Arroyo de la Vegas de los Tanos	24.0	2.9
Arroyo Tonque	179.5	7.1
Arroyo Maria Chavez	11.0	4.7
Las Huertas Creek	47.3	3.8
Jemez River	1039.0	10.5
Arroyo de los Gerencos	25.8	2.6
Arroyo de las Callabacillas	100.8	1.8
Abo Arroyo	358.4	5.8
Rio Puerco	7188.8	5.0
Salas Arroyo	63.9	4.4
Arroyo los Alamos	60.5	4.5
Canada Ancha	4.1	2.7
Rio Salado	1419.3	6.8
Arroyo Rosa de Castillo	4.0	3.1
Arroyo los Alamillo	40.5	4.0
Arroyo de la Parida	39.7	6.5
Arroyo de las Canas	31.0	5.2

There is no question that the bed of a braided river, such as the Rio Grande, is irregular and sediment movement through the channel must be complex. Using a specific gage plot of discharge at the San Felipe gaging station, it was possible to show bed variations of about 1 foot at a constant discharge (Schumm et al., 1984). This is a small variation, but it could involve large quantities of sediment as channel dimensions change. Lagasse (1980) also showed that there could be variations in thalweg elevation up to 5 feet over short periods of time.

Using data from the USGS's 37 cross sections located between Cochiti and Isleta (Dewey et al., 1979), an analysis of the thalweg elevations for the period of record (75 months) revealed some trends of interest (**Figure 3.79**) (Schumm et al., 1984). A rise in thalweg elevation (A' to B') occurs below approximate river mile 10 between months 20 and 35 (August 1971 through November 1972). This correlates with a relatively dry period during which average monthly discharge was low (**Figure 3.80**).

A significant decrease of thalweg elevation follows, and this is probably due both to the major runoff event of early 1973 (Figure 3.80) and to the closing of Cochiti Dam in November 1973 (month 47). Storage of sediment occurred during the dry years, and much of it was removed during the year of high discharge.

The undulations of the thalweg high and the regularly spaced highs at the end of the record in 1975 (Figure 3.79) suggest downstream movement of sediment, as the high points shift downstream with time. Also, they were attenuated. For example, the high on the ridge (20 months) at about 14 miles may be associated with the high (30 months) at about mile 20 and the low bulge (75 months) at mile 26.

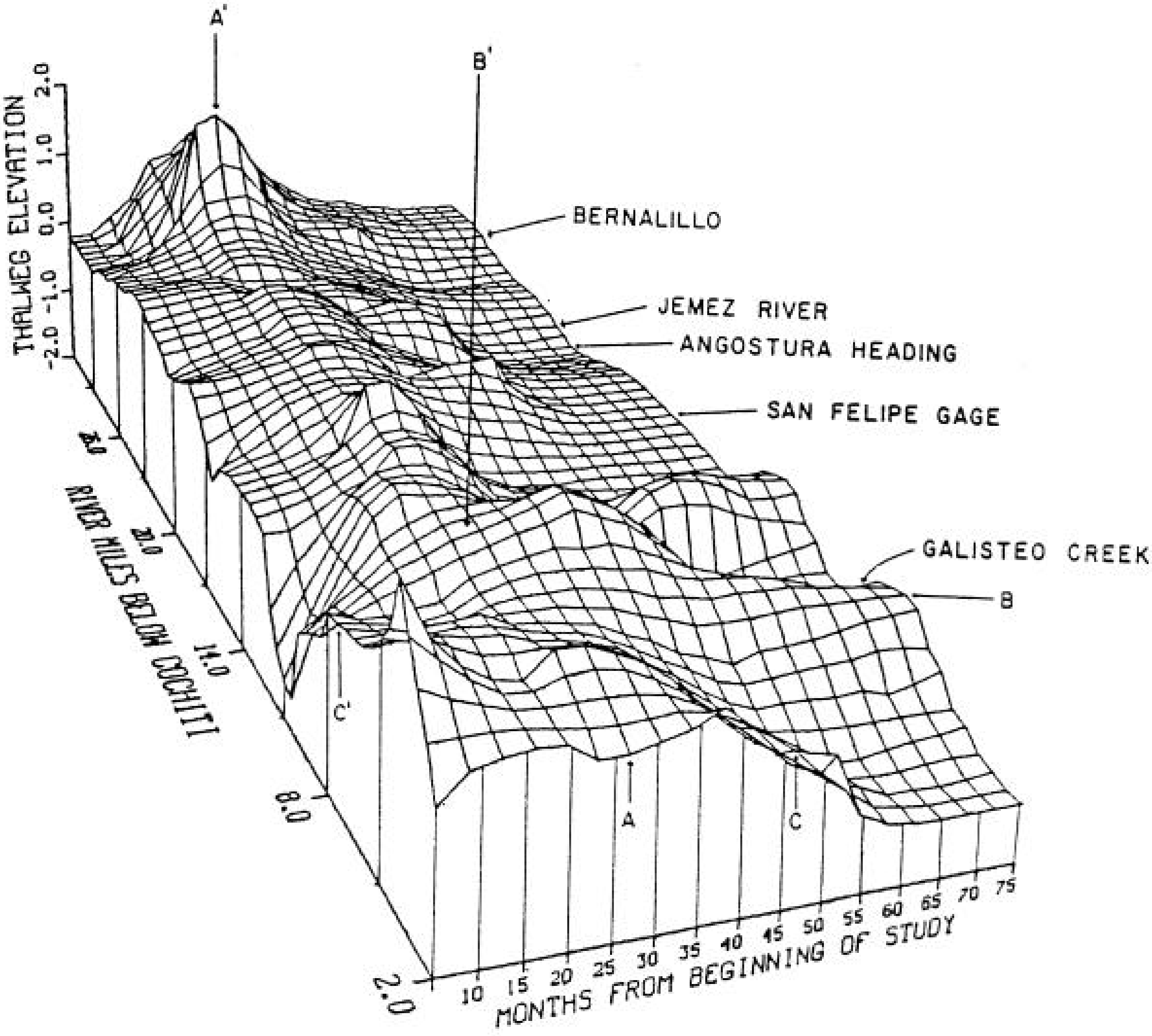


Figure 3.79. Three-dimensional plot of relative thalweg elevations of Rio Grande from Cochiti to Isleta (Schumm et al., 1984). Data are from Dewey et al. (1979).

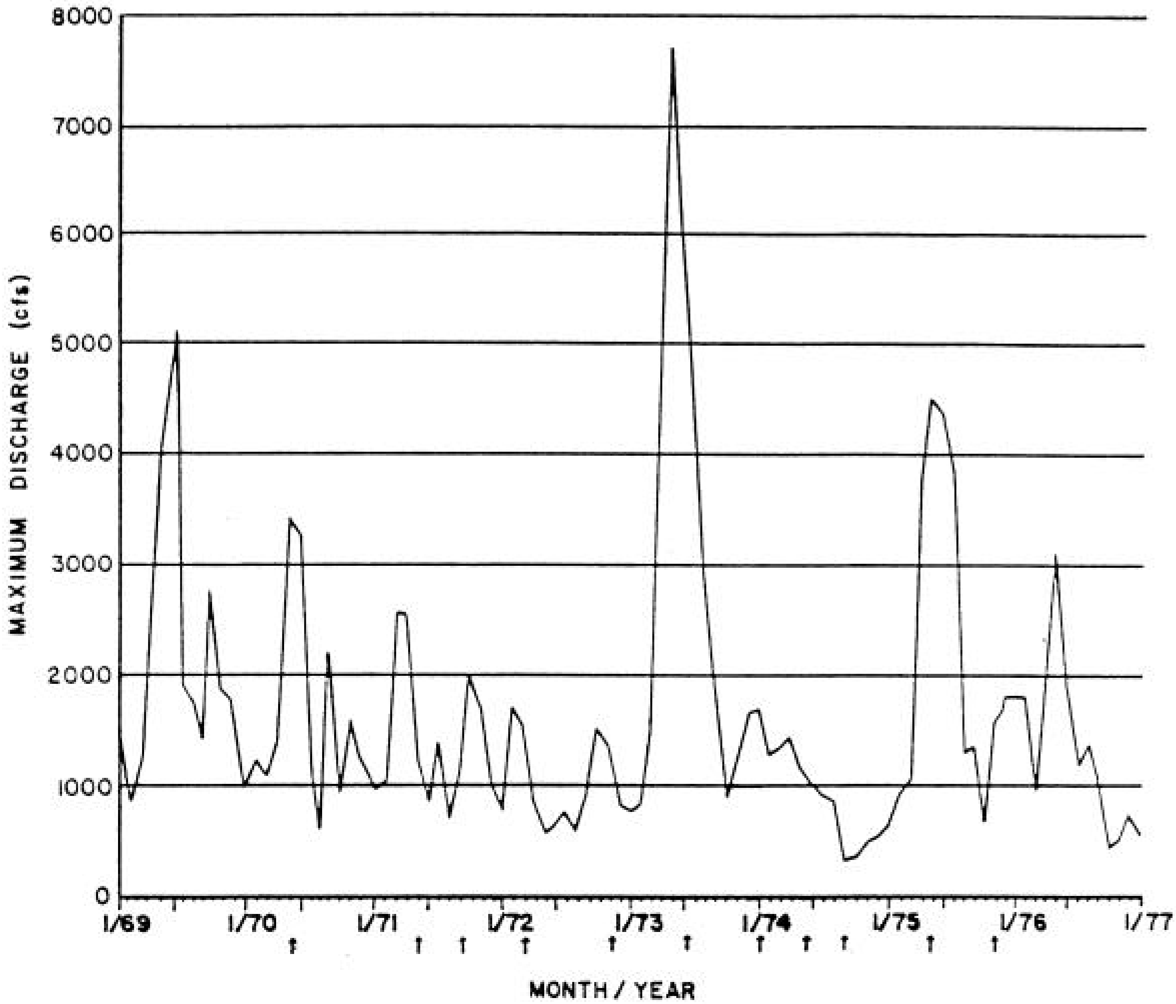


Figure 3.80. Monthly maximum discharge hydrograph for the San Felipe gage. Arrows indicate time of resurveys of the cross sections (Dewey et al., 1979).

At about mile 10 (B' to B), the surface is characterized by a large ridge, which runs diagonally across the plot. This ridge is an area of higher thalweg elevations, and it indicates a zone of aggradation, which appears to be moving upstream. This may reflect a backfilling phenomenon upstream of the Galisteo Creek confluence, which demonstrates a tributary effect on the mainstem river.

In general, deposition is initiated by a decrease in channel slope, which reduces the transport capacity of the flow. This may result from change in sediment and water discharge as during the 1972 dry period. Deposition at a cross section will increase channel slope downstream of the deposit and decrease slope upstream of the deposit to form a channel convexity. The convexity, in turn, causes more deposition upstream and erosion may occur downstream on the steeper reach. This could cause the zone of major deposition or the convexity to migrate.

The sand-bed channel of the Rio Grande is very dynamic. During the period of record, sediment accumulated during relatively dry periods, and it was eroded during wet years. The bed elevation can change drastically with time, and as shown in Figure 3.79, there is a great deal of variability both at one location through time and along the channel at one time.

Lane and Borland (1954), after studying the effects of the 1948 flood, concluded that the *"bed of the Rio Grande (in general) scours at the narrow sections, and that most of the material thus removed is deposited in the next wide section downstream. This action causes the wide section to fill up somewhat and occasionally promotes channel changes in the wide sections which may cause the stream to attack the bank."* These observations by Lane and Borland (1954) support the concept of episodic sediment movement and variable response of the channel from reach to reach.

3.6. Human Impacts

Construction of dams and diversions have had a significant impact on water discharge and sediment loads. Past modifications of river flow and sediment load were designed to reduce or reverse aggradation, which threatened to cause flooding of Albuquerque and other locations. The problems commenced in the 1880s as arroyo cutting delivered large amounts of sediment to the Rio Grande (Elliott, 1979; Happ, 1948; Gellis et al., 1991). In addition, heavy grazing and other agricultural activities contributed to increased flood peaks and increased sediment loads (Harper et al., 1943; Scurlock, 1998). All of these changes caused modifications of the Rio Grande channel. For example, aggradation was a major problem (Harper et al., 1943). From 1880 to 1924, the bed rose 7 feet at the Isleta Bridge and 9 feet at San Marcial (Happ, 1948). According to Lagasse (1980), the Rio Grande was aggrading at a rate of 2 feet in 50 years near Albuquerque, and the riverbed was 6 to 8 feet above the floodplain. Aggradation was 16 feet in 50 years near San Marcial. In 1946, about 37 million tons of sediment was transported by the Middle Rio Grande, but about 25 M tons were deposited in the valley (Scurlock 1998, p. 281). The aggradation not only increased flooding, but it raised the water table causing swampy conditions and loss of agricultural land (Harper et al., 1943).

In the Middle Rio Grande Valley, there was a reduction from 125,000 acres of irrigated land in 1880 to just 40,000 acres of irrigated land by 1925 (Crawford et al., 1993). This decline in agriculture in the Middle Rio Grande Valley prompted Congress to authorize the Rio Grande Reclamation Project in 1905 (Leon, 1998). This project was responsible for the construction of Elephant Butte Dam, which was completed and began operation in 1915 (Lagasse, 1980). This project guarantees the delivery of water to Mexico and the irrigation of 15,000 acres of land in New Mexico and Texas (Burkholder, 1928). The Rio Grande Project also included the construction of water diversion and delivery facilities for irrigation in the Middle Rio Grande Valley (Lagasse, 1980).

In 1925, the Middle Rio Grande Conservancy District was founded by the State of New Mexico and it was responsible for establishing diversions, draining fields, and dealing with existing problems in the valley. By 1935, the district had constructed El Vado Dam on the Rio Chama, as well as diversion dams at Cochiti, Angostura, Isleta, and San Acacia. The district also completed more than 180 miles of riverside drains and 160 miles of interior drains that irrigated a significant, but unquantified acreage. As part of the drain project, linear piles of spoils were placed between the riverside drains and the river. These piles followed the existing river planform and eventually became levees that were used for flood control (Graf, 1994). The design consisted of a floodway that averaged 1,500 feet wide between 8-foot levees (Lagasse, 1980). The levees were built to withstand a design discharge of 40,000 cubic feet per second and the levees, near the City of Albuquerque, were raised to pass a design flow of 75,000 cubic feet per second (Woodson and Martin, 1963).

High flows in 1941 and 1942 with discharges over 21,000 cubic feet per second persisted for several months. These high flows caused severe damage in the valley. As much as 50,000 acres (Scurlock, 1998) were inundated as the levees were breached in 27 different locations (Graf, 1994). After these devastating floods the Bureau of Reclamation and the Army Corps of Engineers devised the Rio Grande Comprehensive Plan (Lagasse, 1980). The Comprehensive Plan called for the construction of a system of reservoirs on the Rio Grande and its tributaries, as well as the rehabilitation of the floodway constructed by the Conservancy District. The Army Corps of Engineers constructed the reservoir system and the Corps with the Bureau of Reclamation (Woodson and Martin, 1963) conducted the floodway rectifications (**Figure 3.81**).

The initial plan, which was approved in 1948, called for the construction of two reservoirs, Abiquiu and Jemez. A later study in 1958 concluded that two additional dams should be built. The additional dams were placed on Galisteo Creek and on the mainstem of the Rio Grande on lands of the Cochiti Pueblo at the head of the Middle Rio Grande Valley (Woodson and Martin, 1963).

Beginning in the 1950s, the Bureau of Reclamation began an intensive data collection program in order to properly implement channel rectification measures. The goal of the program was to determine the design width for the rectified channel. The process of finding the design width included detailed studies of sediment transport and the relationship between hydraulic properties and sediment transport. The study also focused on finding the rates and volumes of aggradation and/or degradation within the river and floodplain (Pemberton, 1964).

The Corps of Engineers completed the Jemez Canyon Dam in 1953, Abiquiu Dam on the Rio Chama in 1963, Galisteo Dam in 1970, and Cochiti Dam in 1973. Cochiti Dam was intended for flood-control and sediment detention. By creating a permanent pool of 50,000 acre-feet behind the dam, almost all sediment entering Cochiti Reservoir is trapped. The sediment detention was intended to prevent further aggradation below Cochiti Dam and the clear-water discharges induced degradation below the dam (Lagasse, 1980).

The channel rectification plan had several stages. First of all, the levees had to be protected to prevent future flood damage. Second, the channel area was to be reduced. A reduction in channel area would reduce water losses and improve sediment and hydraulic transport capacity. Channel rectification was carried out from Cochiti Dam to just above the Rio Puerco and the design capacity was reduced to 20,000 cubic feet per second except in Albuquerque where the design capacity was reduced to 42,000 cubic feet per second (**Table 3.13**). The

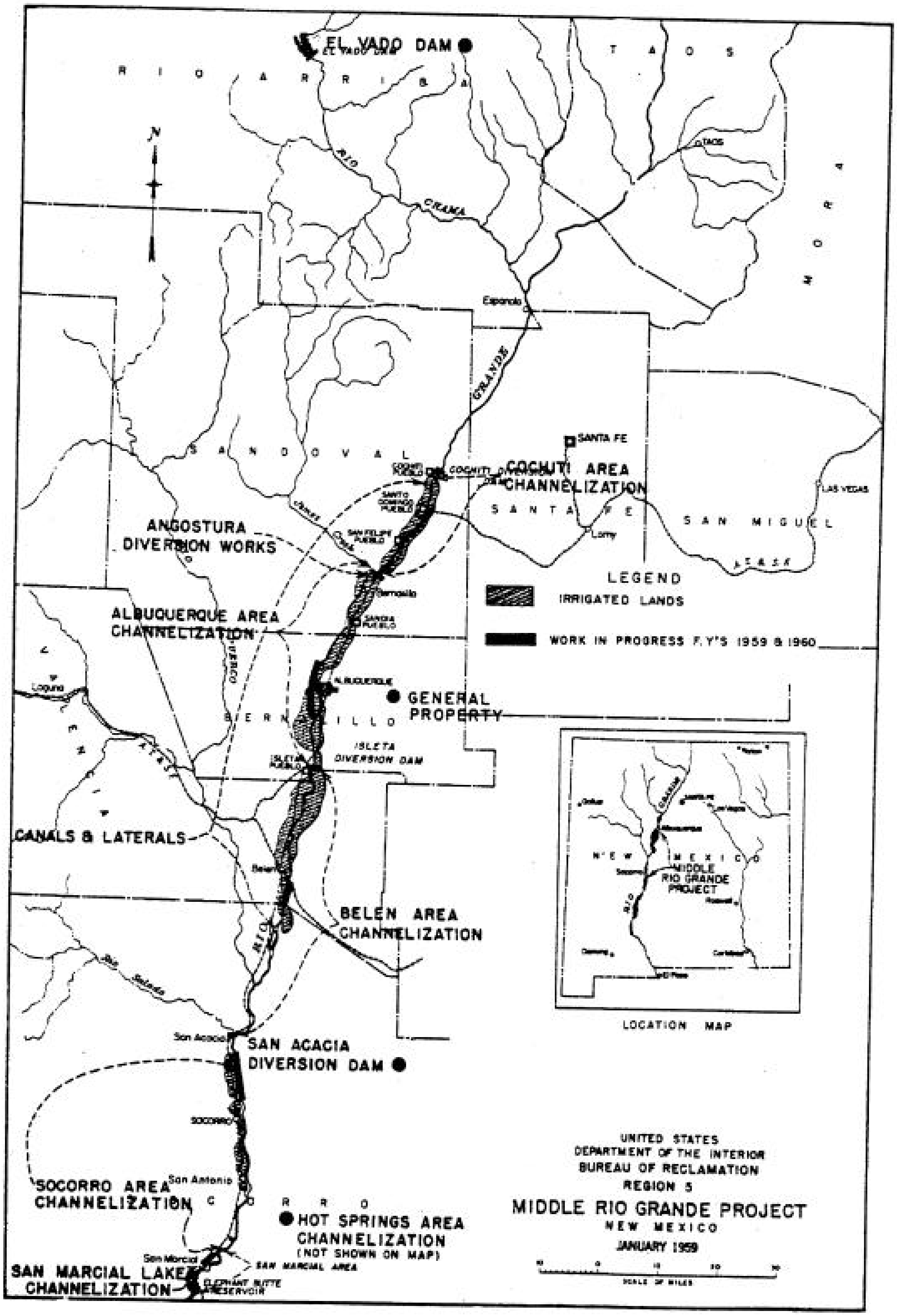


Figure 3.81. Map showing the extent of modification of the Middle Rio Grande for the purposes of irrigation and flood control (COE, 1963).

Table 3.13. Description of Middle Rio Grande conveyance system and channel improvement works (Crawford et al., 1993).

Cochiti to Angostura	
Floodway width	70-1,400 m *230-4,720 ft)
Channel width (average)	91 m (300 ft)
Cleared floodway	No active clearing
Channel stabilization type(s)	Jetty jacks, in situ riprap, pilot channel
Channel stabilization period	Jetty jacks 1953-1974, riprap 1985-present
Angostura to Isleta	
Floodway width	75-920 m (250-3,020 ft)
Channel width (average)	183 m (600 ft)
Cleared floodway	183 m (600 ft)
Channel stabilization type(s)	Jetty jacks, pilot channels, arroyo plug removal
Channel stabilization period	1953-1975
Isleta to San Acacia	
Floodway width	150-930 m (500-3,060 ft)
Channel width (average)	60-305 m (200-1,000 ft)
Cleared floodway	185 m (600 ft)
Channel stabilization type(s)	Jetty jacks, pilot channels, arroyo plug removal
Channel stabilization period	1953-1974
San Acacia to San Marcial	
Floodway width	245-1,495 m (800-4,900 ft)
Channel width (average)	30-305 m *100-1,000 ft)
Cleared floodway	No active clearing
Channel stabilization type(s)	Jetty jacks, pilot channels, arroyo plug removal
Channel stabilization period	Jetty jacks 1953-present

width of the river was reduced from roughly 800 to 500 feet by placing lines of jetties (**Figure 3.82**). Some jetties were projected out from the levees into the flow while others were placed parallel to the levees (**Figure 3.83**). The installation of the Kellner jack jetties began in 1954 and continued intermittently until 1962 when a total of 115,000 units had been installed (Lagasse 1980).

Kellner jack fields, dredging in levees, and bank stabilization have produced a narrower and deeper channel (Figure 3.82). In addition, the channel was straightened by cutting off of large bends. The low-flow conveyance channel (LLFC) was constructed between San Acacia Diversion and the upstream end of Elephant Butte Reservoir with the objective of more efficiently delivering flows downstream. From its completion in 1959 to about 1985, it conveyed most of the flows (Crawford et al., 1993).

The result of these activities was that the Middle Rio Grande narrowed by about 50 percent (Crawford et al., 1993). Obviously, the modern river owes more of its present morphology to human activities than to natural processes (Lagasse, 1980, 1994; Hyrarinen, 1963; Thompson, 1965; Woodson and Martin, 1963).

One of the significant river modification procedures was dredging or channelization. This consisted of the trenching through tributary deposits and the cutting off of large bends (Figure 3.82). **Table 3.14** lists the sites of bend removal. The numerous bends removed prior to 1962 and between 1962 and 1972 would very likely be a major impact on the overall channel. Happ (1948) reported that an artificial cutoff reduced the length of the river by about 2 miles. Gradient was steepened as the channel was shortened and headcutting and incision occurred (Happ, 1948). The following discussion concentrates on dredging or channelization as observed on 1962, 1972, and 1992 aerial photographs.

Table 3.14. Locations where bends were removed by dredging between 1962 and 1992 as determined from 1962, 1972 and 1992 aerial photography.

Date	Location (Sta.)	Reach Number
Pre-1962	806117	2
	773578	3
	669922	3
	584771-579060	3
	419056-411432	5
	398638-391380	5
	25331-246200	6
1962-1972	886406	1
	883279	1
	880716	2
	873192	1
	841134-828520	1
	825843	1
1972-1992	884144-882472	1

Figure 3.82. Aerial view of a completed jetty system, including a dredged pilot channel on the Middle Rio Grande (COE, 1963).

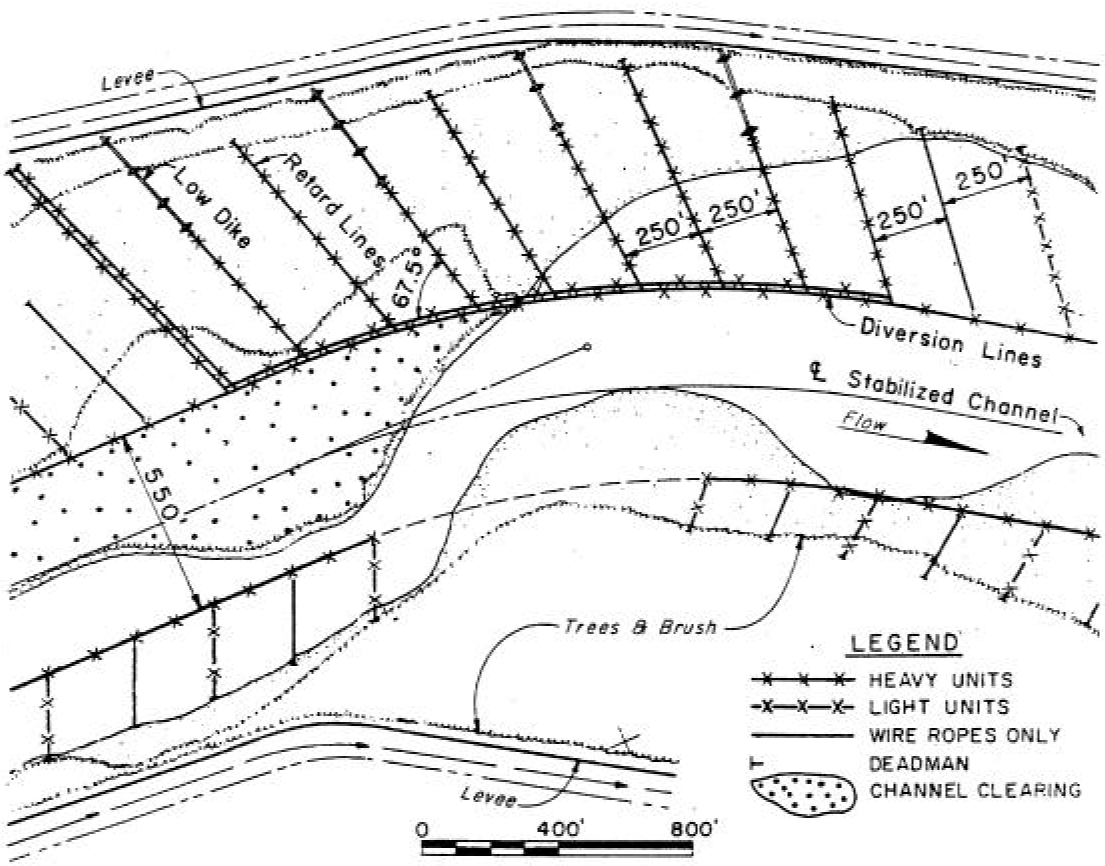


Figure 3.83. Typical layout of jetty system on the Rio Grande Floodway, Cochiti to Rio Puerco Unit (COE, 1963).

Starting at about Sta. 889290, the wide 1962 channel was dredged and straightened to Sta. 862845. This involved cutting off large bends at Stations 886406, 883279, 880716, 873192, 870585, and the closing of side channels (Stations 888308, 881836, 879692, 876457, 871017).

However, in 1992, the dredged channel had developed a sinuous pattern (Sta. 889290 through Sta. 879692).

In 1972, the Rio Grande at the mouth of Galisteo Creek to Sta. 862845 was dredged, apparently through the sediment delivered from Galisteo Creek. This reach has remained straight to 1992.

In 1992, the Rio Grande downstream of Santo Domingo Canyon was sinuous, but in 1962, the reach (Sta. 853232 through Sta. 848935) was dredged to form a straight channel through a large sediment deposit. In 1992, this reach was sinuous.

In 1972, a large bend (Sta. 841134 through Sta. 838520) was cut off by dredging. In 1972, a smaller bend had formed at this location.

In 1972, a large bend (Sta. 825843) was cut off and downstream the river was confined (Sta. 824660 through Sta. 813478) at the San Felipe constriction.

In 1972, a large bend (Sta. 806117) was cut off probably by dredging. In 1992, the river was straight.

In 1962, a large bend (Sta. 806117) appears to have been cut off by dredging. In 1972, the channel was narrower and was of generally uniform width from San Felipe to upstream (Sta. 786805) of the Jemez River. The Jemez Reservoir was in operation in 1953, nevertheless, the river widened at the confluence to Sta. 778511, where it narrowed probably as a result of dredging prior to 1962.

In 1962, a large bend (Sta. 773578) was cut off by dredging and there appeared to be a narrow dredged channel from Sta. 779053 to Sta. 765001. In 1972, the river from about Sta. 773578 was of uniform width, and it appeared controlled to Sta. 733504, where it widened.

In 1962, the river was wide and variable to about Sta. 693925, where a system of jacks narrowed the river to about Sta. 676291. A large bend (Sta. 669922) was cut off by 1962. In 1972, the river appeared controlled in this reach by dikes.

In 1962, the river was variable in width to Sta. 621173 with some effects of dredging(?) and dike fields. The river in 1972 was of relatively equal width and it was clearly controlled by dikes. In 1992, the river was narrower than in 1972, but otherwise the same. In 1962, three bends were cut off by dredging (Sta. 584771 to Sta. 579060, upstream of Isleta Diversion).

In 1962, river width was variable with obvious effects of dikes and dredging. There was narrowing of the river, apparently by dredging at Sta. 572466 and Sta. 568057 to Sta. 561204, and perhaps elsewhere, but clearly at Sta. 541528 to Sta. 534498, Sta. 498151 to Sta. 495052, Sta. 467354 to Sta. 450729, and Sta. 421279 to Sta. 411432. A large bend was cut off at Sta. 419056 to Sta. 411432. At Sta. 398638 to Sta. 391380, a large bend was cut off. In 1972 and 1992, the river had a relatively uniform width, which was controlled by dikes.

The river widened upstream of Rio Puerco at Sta. 398638 to Sta. 396451 in 1962. There was a narrow dredged channel at Sta. 374436 to about Sta. 369999 in 1962, which extended to the Rio

Puerco in 1972. The channel was very wide in 1992. Channel was narrow and probably dredged in 1962 (Sta. 346218 to Sta. 341988).

A narrow dredged channel in 1972 at Sta. 330757 to Sta. 324950 cut off the main channel. In 1992, the river followed this dredged course. The channel was dredged in 1962 and 1972 (Sta. 295279 to Sta. 290802). The river was very wide in 1962 and 1972 (Sta. 281614), but narrow in 1992 to Sta. 273546, then it greatly widened. In 1992, the channel was narrow and dredged from Sta. 252378 to Sta. 238715.

In 1962, a very large bend was cut off (Sta. 253331 to Sta. 246200). In 1962, the channel was very wide probably as a result of deposition downstream of the Belen-Socorro Uplift. In 1992, it was dredged from Sta. 233642 to Sta. 231266.

The wide river narrowed at Sta. 172661 in 1962 and 1972. There was a uniform width to Sta. 164173, then it widened to Sta. 146988. It was very narrow in 1992 to Sta. 146988, then very wide to Sta. 118948. A very narrow 1992 channel, which was probably dredged, extended from Sta. 107136 to San Marcial.

Most bend removal occurred prior to 1962, but dredging to maintain a narrow relatively straight channel continued between 1972 and 1992. As noted above, bend removal would have steepened the channel, and it should have had a significant impact on the channel upstream by degradation and downstream by deposition. Dredging through sediment deposits that apparently were blocking the channel clearly modified the hydraulics of that reach. In short, human activities downstream of Cochiti Dam undoubtedly had a major impact on the Rio Grande.

4. CHANNEL CHANGES THROUGH TIME

Changes in hydrology and sediment supply, as well as man-made modifications have caused significant changes in the morphology of the Middle Rio Grande between Cochiti and Elephant Butte Reservoir. Baird (2001) has argued that because the Middle Rio Grande Valley has been aggrading for the last 11,000 to 22,000 years, the system was not in a state of dynamic equilibrium (Schumm and Lichty, 1963), but all fluvial systems tends to be net aggradational over time (Bridge and Leeder, 1979; Allan, 1985). However, Hawley (cited in Crawford et al., 1993) considers that there is no evidence that the general morphology of the Middle Rio Grande Valley has significantly changed over the past 5,000 years. It is important to recognize the distinction between valley and channel equilibrium, and that even if the system is net aggradational, the channel can still be in a state of dynamic equilibrium (Leeder, 1978). There is no evidence to indicate that the river was not in a state of dynamic equilibrium prior to the onset of man-made changes. The changes in the planform characteristics of the river in the 9 identified reaches are discussed in Section 2.2. Man-made interventions including, importations of water, the water-supply and flood-control reservoirs, diversion structures on the river, the flood-control project and the water conveyance project, have been reported (Lagasse, 1980; Leon, 1998; Bauer, 2000; Richard, 2001; Baird, 2001; Smith, Makar and Baird, 2001) to cause changes in (1) channel width, (2) thalweg elevation, (3) the ability of the river to migrate laterally, (4) the capacity of the channel, and hence the frequency of overbank flooding, (5) local sediment storage and bar morphology, and (6) bed-material composition.

4.1. Changes in Channel Width

Using Schumm's (1977) qualitative model of channel changes that result from changes in hydrology and sediment supply, Baird (2001) concluded that the documented changes in channel width since 1962 are consistent with changes in the flows and sediment loads. The baseline for his conclusion are the average widths for identified reaches derived from the 1917-1918 survey. Average 1992 widths range from about 23 to 35 percent of the historic (1917-1918) widths. However, his data (Baird, 2001, Table 2) clearly show that the majority of the channel narrowing took place between 1917-1918 and 1962, and this was caused primarily by channelization of the river. Interpretation of any changes that took place between 1962 and 1992 is confounded by the changes in hydrology and sediment supply that occurred in the early-mid 1970s, and by the underlying assumption that the river had completed its responses to the channelization, and was thus in a state of equilibrium prior to the commencement of the hydrologic and sedimentologic changes caused by the dams. Review of the 1917-1918 maps of the river, and the 1962, 1972 and 1992 aerial photography indicates that regardless of the reach being considered, or the time period, the width of the river is extremely variable, and therefore, the use of reach average values tends to mask changes through time. For example, Figure 2.10 shows the mean width values for each of the nine subreaches from the 1917-1918 maps, but it also shows the minimum and maximum values, which are highly variable.

In order to determine how channel width has changed between 1962 and 1992, 140 cross sections were selected from the total of about 1,800 range lines. The selection was based on uniformity of width. That is, when width was relatively unchanged along the river only a few range lines were selected for analysis, but where width changed significantly downstream many more range lines were selected for the analysis (**Figures 4.1a and 4.1b**). The data in Figures 4.1a and 4.1b show that width has varied greatly along the river and with time between 1962 and 1992. It is significant that depending on location, the river has both widened and narrowed between 1962 and 1992. Changes of width between 1962 and 1992 are shown on **Figure 4.2**. Changes of width were relatively minor between Cochiti Reservoir and the US Highway 60

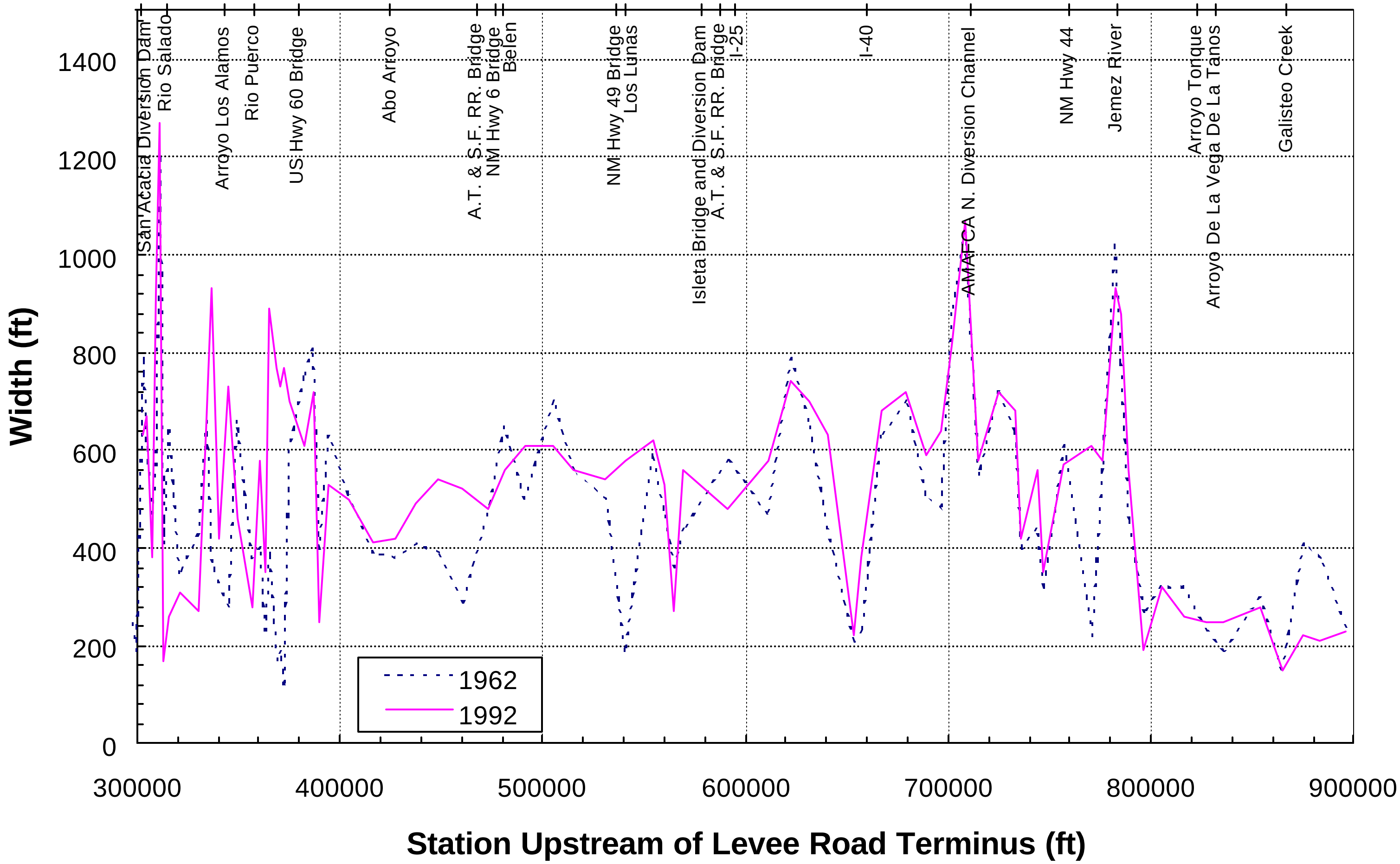


Figure 4.1a. Channel widths between San Acacia and Cochiti Reservoir plotted against station for 1962 and 1992 periods.

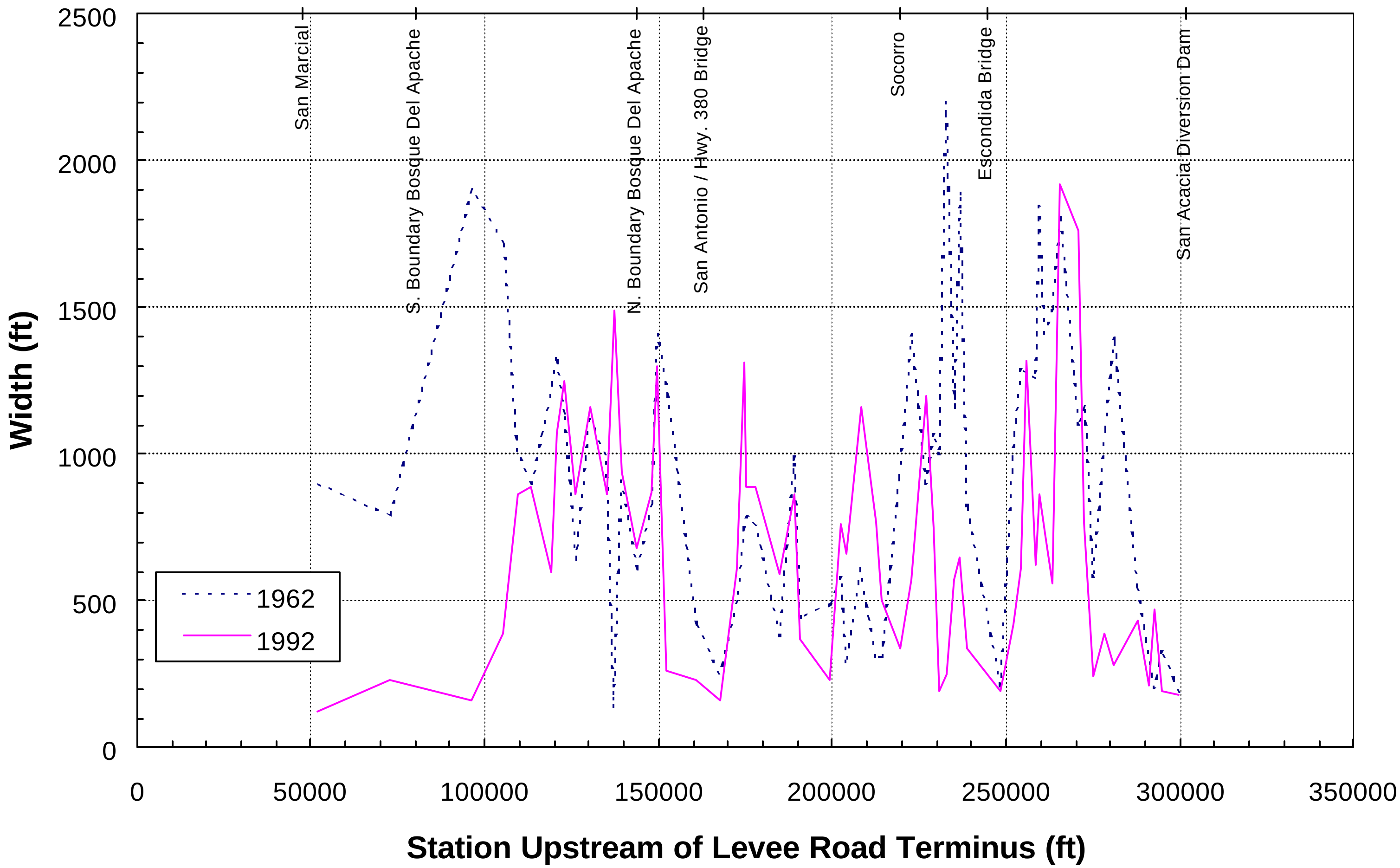


Figure 4.1b. Channel widths between San Marcial and San Acacia plotted against station for 1962 and 1992 periods.

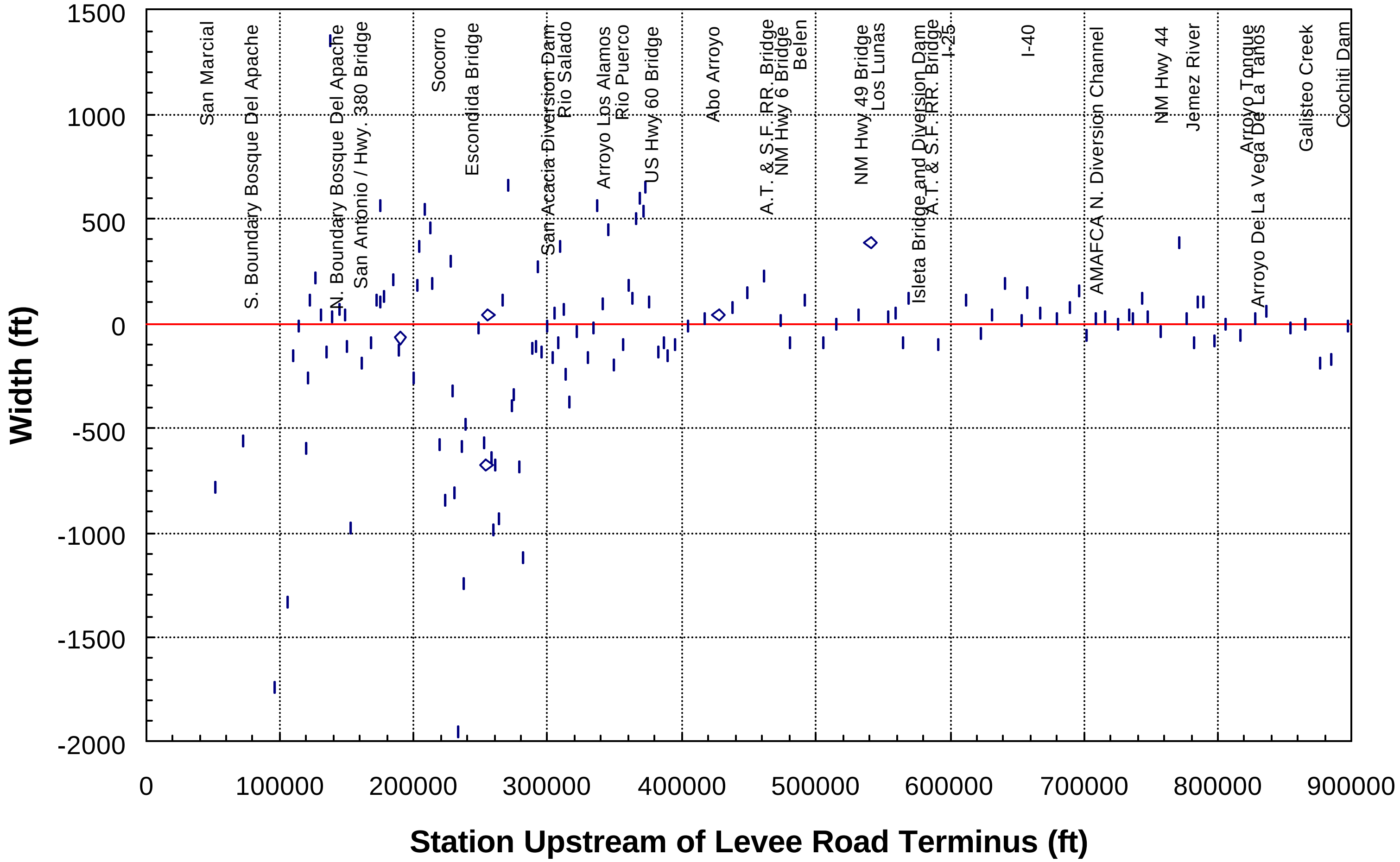


Figure 4.2. Changes in channel width between 1962 and 1992 plotted against station between San Marcial and Cochiti Reservoir. Positive values indicate an increase in width and negative values indicate a decrease in width.

crossing at Bernardo (Reaches 1,2,3, and 4a), but widening was more common than narrowing. In Reach 5 (Bernardo to San Acacia) there was both widening and narrowing of the channel. Channel narrowing predominated in Reach 6 (San Acacia to Escondida), and there was both widening and narrowing in Reach 7(Escondida to San Antonio). Between San Antonio and the Middle of the Bosque del Apache NWR there was both narrowing and widening, but downstream of the Bosque del Apache; the trend has been channel narrowing.

Channel widths were also measured from the 1917-1918 maps (at the location of each 2-foot contour interval) and the 1972 and 1992 aerial photography (every 5^{th} range line). **Figure 4.3** shows the mean width and the standard deviation about the mean for the nine subreaches in 1917-1918. There is an expected general trend of increasing width from upstream to downstream, but the variability in the width also increases in the downstream direction. The 1972 data (**Figure 4.4**) also show a general trend of increasing mean width in the downstream direction between Cochiti Reservoir and the downstream end of the Bosque del Apache (Reach 8a), where the channel width narrows considerably as a result of it being a completely man-made channel. The variance in the width is much less in the five upstream Reaches (1, 2, 3, 4a, 4b), but it becomes much greater in Reaches 5, 6, 7 and 8a. In 1992 the mean width data are more complex (**Figure 4.5**). The major changes occurred in Reaches 5 and 6 where the channel narrowed. As a result mean channel width shows a decrease between Belen and Escondida, but the variance is also high in this Reach of the river.

Table 4.1 summarizes the reach mean widths and the corresponding standard deviations for the three periods (1917-1918, 1972, 1992). The changes in mean channel width between 1917-1918 and 1972 are statistically significant (2-tailed t-test, "=0.1) for all of the Reaches. However, because of the high variance, the only change in mean width between 1972 and 1992 that is statistically significant (2-tailed t-test, "=0.1) is in Reach 6 (San Acacia to Escondida). Since the 1972 and 1992 data represent periods when the hydrology and sediment supply to the river were different, then it is reasonable to conclude that the reduction in mean width in Reach 6 could be attributed to those changes. However, flows have significantly increased in the reach, and since 1985 the flows have been conveyed in the channel rather than the LFCC. There is no doubt that the peak flows have been reduced (Table 3.1). The bed-material rating curves for the San Acacia gage (Figure 3.54) do not show a significant change in the post-dam period, and there has only been a minor change in the suspended-sediment rating curve (Figure 3.47). Therefore, it is difficult to explain the changes in terms of Schumm's (1977) equalities, since the increases in discharge and no significant change in sediment load would normally be expected to lead to an increase in the channel width. A possible explanation is that the channel is degrading, or that the narrowing is more related to the absence of peak flows that has permitted the primarily non-native vegetation to become established. Establishment of a more perennial flow regime since 1985 when the LFCC was not used to convey flows may well have exacerbated the problem of vegetation encroachment (Johnson, 1994).

4.2. Changes in Bed Elevation

Baird (2001) reported a range of reductions in average bed elevations for three Reaches of the Middle Rio Grande. From Angostura to Bernalillo he reported 7.3 feet of average bed elevation lowering between 1971 and 1995, from Rio Puerco to San Acacia he reported 3 feet of average bed lowering from 1962 to 1992, and from San Acacia to Escondida he reports 9.6 feet of average bed lowering between 1962 and 1999. The use of the 1962 baseline presents a problem with respect to interpreting the Baird (2001) data, because the major changes in hydrology and sediment supply occurred in the early 1970s, and there is no doubt that the channelization project was also occurring in some of the Reaches during the period of

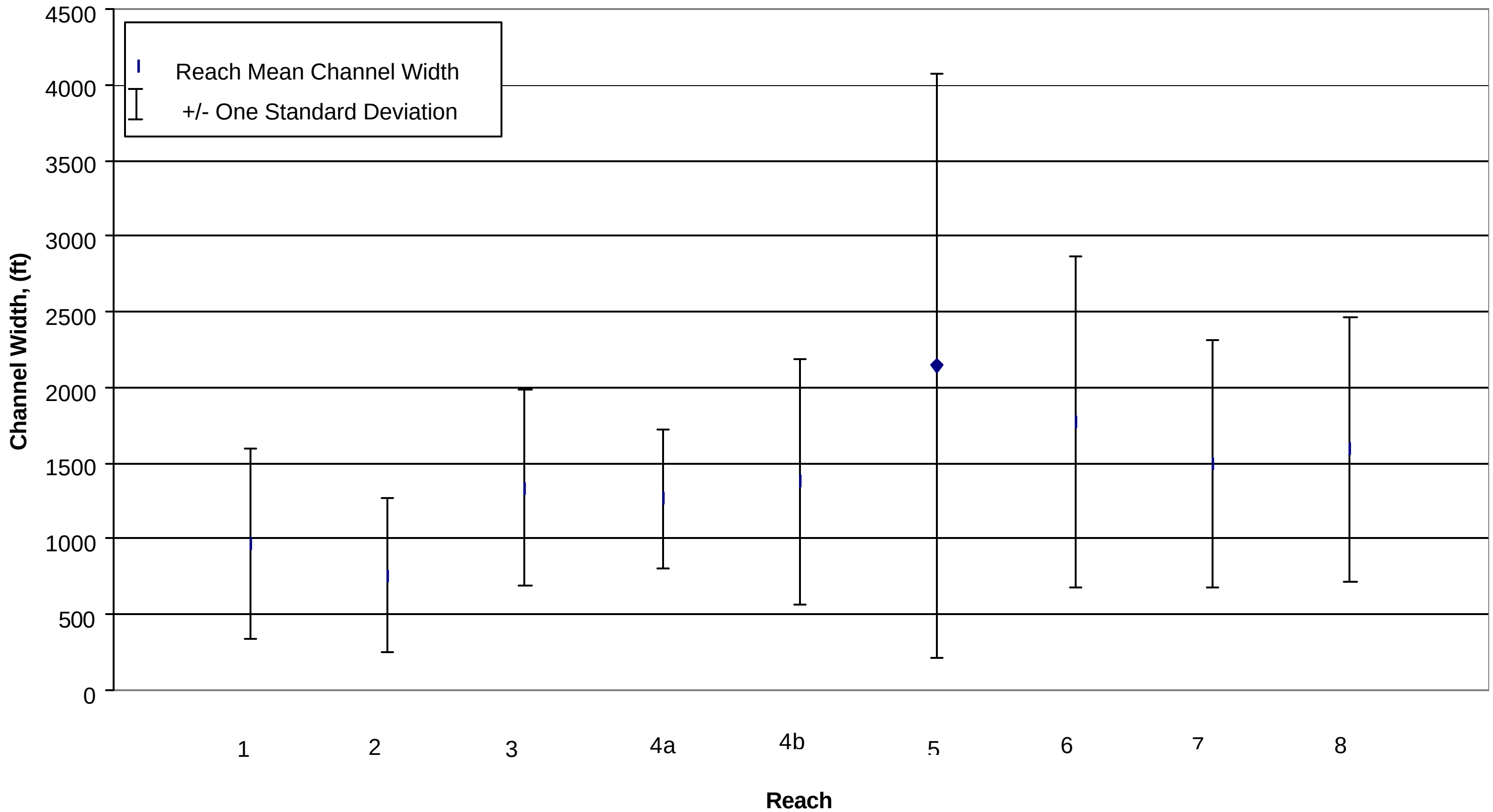


Figure 4.3. 1917-1918 mean widths and standard deviations about the mean for the identified reaches of the Middle Rio Grande.

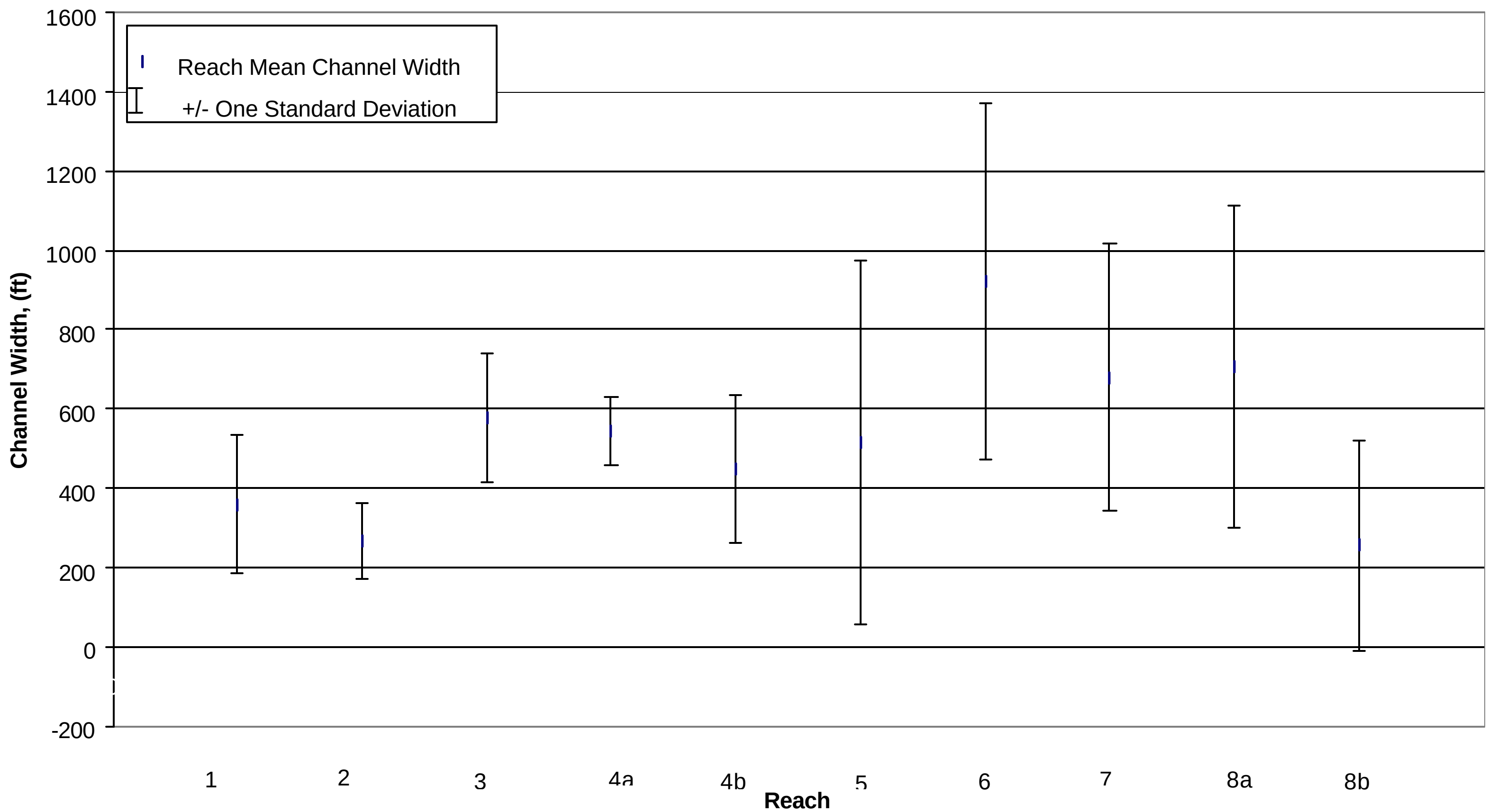


Figure 4.4. 1972 mean widths and standard deviations about the mean for the identified reaches of the Middle Rio Grande.

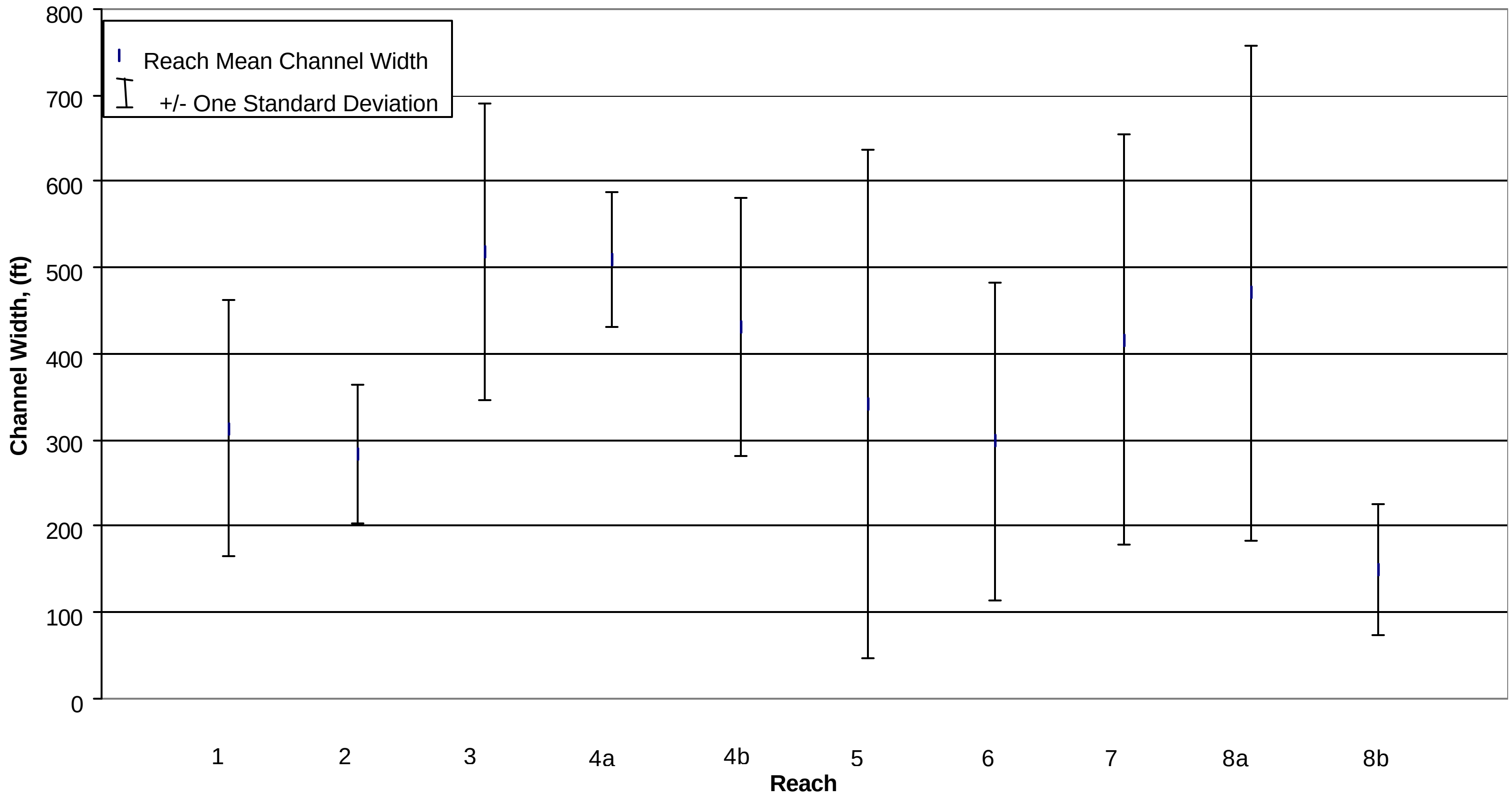


Figure 4.5. 1982 mean widths and standard deviations about the mean for the identified reaches of the Middle Rio Grande.

comparison. Although much of the channelization occurred in the 1960's, it is not likely that the river had completed its responses to the channelization by the time the major flow and sediment supply changes were initiated. Therefore, interpretation of cause and effect should be made with caution.

Table 4.1. Summary of mean channel widths and standard deviations for 1917, 1972, and 1992.

Reach	1917 Maps		1972 Photos		1992 Photos	
	Mean Channel Width (ft)	Standard Deviation (ft)	Mean Channel Width (ft)	Standard Deviation (ft)	Mean Channel Width (ft)	Standard Deviation (ft)
1	968	632	359	173	314	148
2	758	511	267	94	284	81
3	1338	653	577	163	519	172
4a	1263	458	542	86	509	79
4b	1379	807	447	187	431	149
5	2143	1925	514	458	342	296
6	1771	1089	920	449	299	185
7	1492	817	679	337	416	238
8a	1595*	874	706	406	471	287
8b			255	264	149	76

*Reaches 8a and 8b are combined.

Changes in thalweg elevation were determined from a number of sources including Leon (1998) and Bauer (2000), and the USBR range lines (**Figure 4.6**). Between Cochiti Reservoir and Angostura Diversion the comparative thalweg data show that there was general channel degradation of up to about 4 feet, but there were also locations where the channel aggraded in the period from 1973 to 1995. Richard (2001) showed that there was very little degradation between Cochiti Reservoir and San Felipe, most likely because the bed material was coarse and prevented further degradation (Rittenhouse, 1944; Culbertson and Dawdy, 1964; Nordin and Beverage, 1965). In the Reach between Angostura Diversion and about Bernalillo changes in thalweg elevation of up to 8 feet were observed between 1973 and 1998. However, this Reach was channelized in the 1960s and it is highly likely that some of the degradation is the result of continued river response to the initial channelization.

Between Bernalillo and San Acacia the comparative thalweg data (1962-1998) in Figure 4.6 indicate that there was some channel incision as well as locations where the thalweg elevation increased. Most of the incision was less than about 2 feet, as was the aggradation. This Reach of the river was extensively channelized in the 1960s. Local lowering of the thalweg in a sand-bed channel is not inconsistent with the changed flow regime in the reach (Table 3.2; Nordin and Beverage, 1965; Anthony and Harvey, 1991).

Immediately downstream of the San Acacia Diversion there is little doubt that there has been significant lowering of the thalweg between 1962 and 1998. The reach downstream of the Diversion was extensively channelized in the 1960's and this is the most likely explanation for the observed channel degradation between the San Lorenzo Settling Basin and the Diversion. Survey data prior to 1987 were not available for the Reach between San Acacia and San Marcial. However, the available data in Figure 4.6 indicate that the Reach from San Acacia to about the north boundary of the Bosque del Apache NWR was somewhat degradational between 1987 and 1999. Why this reach of the river is degrading is not clear. The volume of

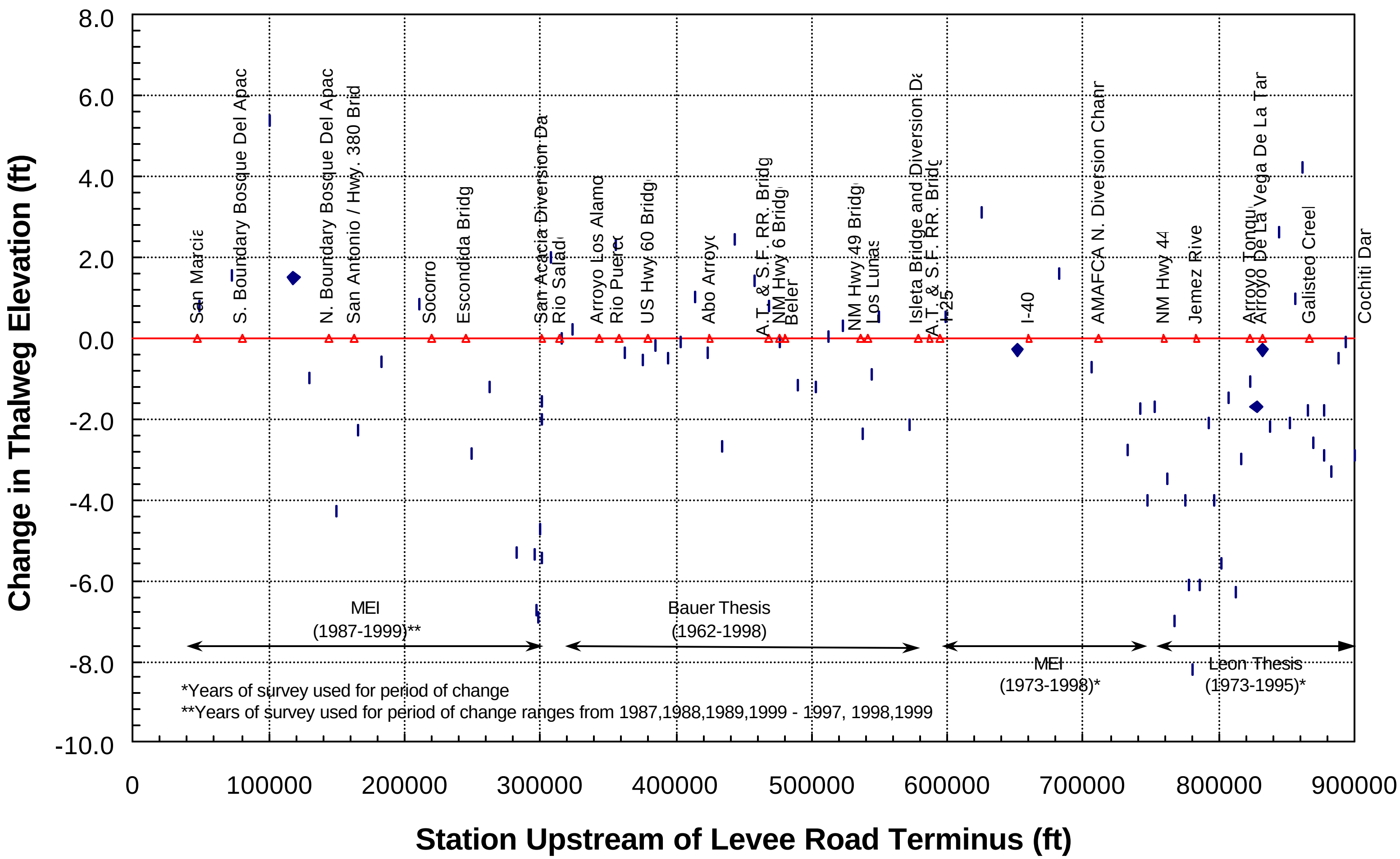


Figure 4.6. Changes in thalweg elevation along the Rio Grande between Cochiti Reservoir and Elephant Butte Reservoir. Positive values indicate aggradation and negative values indicate degradation.

flow in the reach has increased significantly due to a number of factors, including the cessation of flow routing through the LFCC. A possible explanation is related to the fact that most of the flows prior to 1985 were routed down the LFCC and channel narrowing occurred in this Reach when the flows were diverted into the LFCC. Riparian vegetation has encroached into the floodway, and so when the flows were returned to the river the increased hydraulic roughness on the channel margins led to increased in-channel velocities and channel bed degradation (Harvey and Watson, 1988). Downstream of the Bosque del Apache National Wildlife Refuge, there is no doubt that the channel has aggraded (Smith, Makar and Baird, 2001).

Changes in the mean bed elevation were also determined for the various Reaches, since this measure provides a more realistic view of change because thalweg elevations can change rapidly between events (**Figure 4.7**). Between Cochiti Reservoir and Angostura Diversion, the mean bed elevation was reduced by less than 2 feet at most locations between 1973 and 1995 (Leon, 1998). The maximum change in this Reach of the river was about 3 feet. Between Angostura Diversion and Bernalillo, changes in mean bed elevation of between 2 and 4 feet occurred between 1973 and 1995. Between Albuquerque and Isleta mean bed elevation was reduced by up to 2 feet between 1973 and 1998, and this degree of degradation is corroborated by the shift in the discharge-stage rating curves at the Albuquerque gage (Figure 3.40). From Isleta to about Bernardo there appears to have been about 2 feet of bed lowering between 1962 and 1998, but at least some of the lowering is probably related to the 1960s channelization, and the remainder is probably related to local channel adjustments to the changed flow regime (Table 3.2). Between Bernardo and San Acacia, up to 4 feet of bed lowering occurred upstream of the Rio Puerco confluence between 1962 and 1998. The degradation appears to be related to extensive channel narrowing in the same Reach, the result of channelization. There is no doubt that the mean bed elevation decreased significantly in the Reach immediately downstream of the San Acacia Diversion. The data show that up to 12 feet of general lowering occurred in the 1962-1998 period (Bauer, 2000) where the combined effects of sediment trapping upstream of the diversion and the 1960 channelization would be maximized. The amount of degradation in the rest of the reach is on the order of 6 feet.

The situation downstream of the channelized Reach below the San Acacia Diversion is not as clear. Actual river survey data, as opposed to photo-interpreted topography, were not available for the comparable time periods. Actual survey data were available for the 1987-1999 period, and these indicate that there was about 2 feet of general bed lowering from upstream of Escondida to the north boundary of the Bosque del Apache NWR. The survey data encompass the period when the LFCC was not in use, and the magnitude of the results are not inconsistent with in-channel scour caused by increased hydraulic roughness along the channel margins and in the overbanks (Harvey and Watson, 1988). If this interpretation is correct, it suggests that returning flows to the river may have had an unintended consequence. General lowering of the bed by up to 2 feet means that considerably more flow will be required to generate overbank flows that appear to be required for environmental purposes. Downstream of the Bosque del Apache National Wildlife Refuge, there is little doubt that there has been a general trend of between 1 and 2 feet of aggradation of the entire bed of the channel, which is consistent with the conclusions drawn by others (Smith, Makar and Baird, 2001).

Photo-interpreted bed elevations from 1962, 1972 and 1992 were used to develop comparative bed profiles of the Rio Grande from Cochiti Dam to Elephant Butte Reservoir (**Figure 4.8**). The general shape of the individual profiles conforms to that of the bed profile developed from the 1917-1918 survey (Figure 2.10), and the effects of the Belen-Socorro uplift can still be seen on the profiles, even though there has been considerable modification of the channel in the intervening period. At the plotted scale (vertical exaggeration of about 500:1) the more definable changes in the bed profile are apparent. Some lowering of the bed profile has

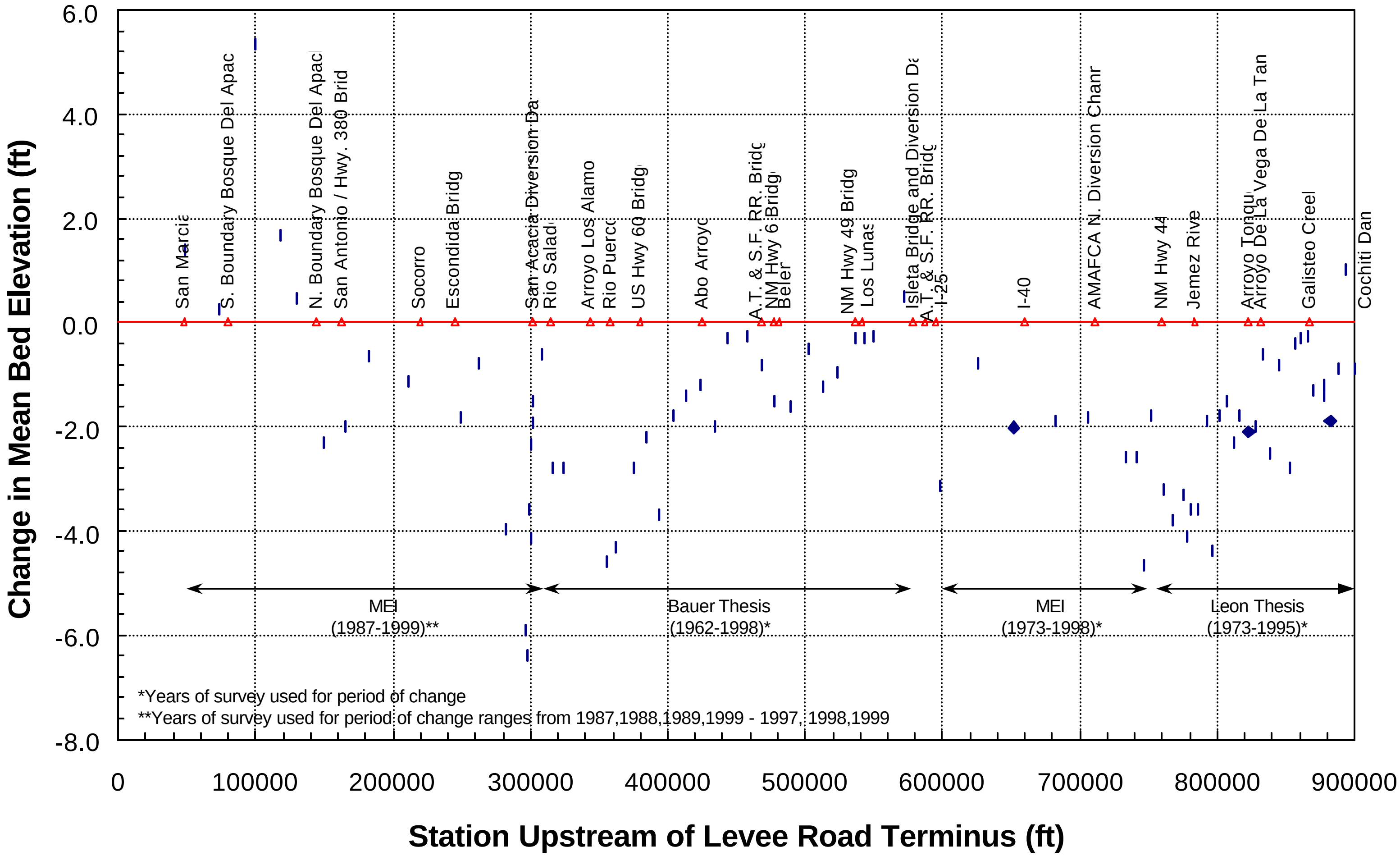


Figure 4.7. Changes in mean bed elevation along the Rio Grande between Cochiti Reservoir and Elephant Butte Reservoir. Positive values indicate aggradation and negative values indicate degradation.

Figure 4.8. Comparative longitudinal profiles of the Middle Rio Grande based on photo-interpreted bed elevations From 1962, 1972, and 1992.

occurred locally in Reach 1 between Cochiti Reservoir and San Felipe, as well as in Reach 2 between San Felipe and Angostura Diversion. Without any doubt there has been a significant lowering of the bed profile between Angostura Diversion and Bernalillo in the upper part of Reach 3. At the plotted scale, it does not appear that there has been very much lowering of the bed profile for the remainder of Reach 3 (to Isleta Diversion), although the discharge-stage rating curves at the Albuquerque gage (Figure 3.40) do show a stage reduction of about 2 feet for discharges up to about 5,000 cfs. Between Isleta Diversion and Belen (Reach 4a) there do not appear to have been significant changes in the bed elevations. Between Bernardo (Reach 4b) and the Rio Salado confluence (Reach 5) there has been some lowering of the bed. A similar situation is apparent between San Acacia Diversion and Escondida in Reach 6. If anything, there has been a slight increase in the bed elevations in Reach 7 between Escondida and San Antonio. A similar situation exists in the upper part of Reach 8 between San Antonio and the Bosque del Apache NWR. Downstream of the Bosque, the bed elevations have increased significantly (Smith et al., 2001).

4.3. Changes in Lateral Migration of the Channel

Descriptions of channel change by early residents of the Middle Rio Grande Valley indicate that the Rio Grande was subject to channel shift and avulsion. Early descriptions of change tended to be concentrated near towns, where of course, channel change was most destructive. For example, Scurlock (1998) cites channel change at several towns during large floods in the 18th and 19th centuries (**Table 4.2**). Also, a railroad surveyor noted in 1870 that the cottonwood Bosque was periodically removed by floods (Scurlock, 1998). The 1935 aerial photographs of the river between San Acacia and Elephant Butte Reservoir clearly show evidence of destruction of the riparian vegetation (**Figure 4.9**) and a cutoff of a channel bend (**Figure 4.10**) as a result of the floods of the early 1930s. Clearly, channel shift was common throughout the Middle Rio Grande prior to implementation of the flood-control projects in the 1930's. Significant channel shift and attendant bank erosion and sediment deposition also occurred in large floods into the 1940s (Happ, 1948).

Table 4.2**.** Historical locations of lateral changes in the Rio Grande (Scurlock, 1998).

Date	Location
1700	Bernalillo
1735	Bernalillo
1769	Tome
1850	Corrales
1865	Mesilla
1974	Numerous locations
1884	Los Lunas
1885	Rincon

Figure 4.9. 1935 aerial photograph (#5909A) of the Rio Grande between Escondida and San Antonio showing the destruction of riparian vegetation by the floods of the early 1930s (RM 96-RM 101).

Figure 4.10. 1935 aerial photograph (#5927A) of the Rio Grande downstream of San Lorenzo showing the cutoff of a bend following the floods of the early 1930s (RM 112-RM 114).

Richard (2001) conducted the only evaluation of bankline changes that has been reported. Bankline changes from 1918 to 1992 were summarized for the reach of river from Cochiti to Bernalillo. She concluded that bankline erosion was a maximum between 1918 and 1935, but it decreased significantly between 1935 and 1949, and then decreased less rapidly to 1985-1992. The rate of bank erosion was most probably correlated with the occurrence of the floods in the late 1920s and early 1930s (Figures 3.5, 3.6, and 3.7). Given that there were similar floods throughout the river in the same time periods, as well as in the early 1940s (Figures 3.8, 3.9, 3.10, and 3.11), it is reasonable to conclude that the river was as laterally active downstream of Bernalillo. Happ (1948) reports significant bank erosion along the river between Cochiti and Elephant Butte Reservoir following the floods of 1937 and 1941.

Baird (1998) states that after the construction of Cochiti Dam and the resulting channel degradation the river changed from a sand to a gravel- and cobble-bed channel and "*the channel has sought to become longer through bank erosion and meandering in many areas as degradation has progressed over time".* This statement implies that the rate of bank erosion should be increasing again, but Richard's (Figure 5.5; 2001) data do not support Baird's (1998) contention. However, it is also possible that there has been increased bank erosion since 1992, but there were no exceptional flood events in the intervening period (Figure 3.5), and supporting data were not presented. Local reaches of eroding bank will always be present along any river, unless the river is totally channelized and protected. However, the causes of the erosion are likely to be locally controlled, and there is no way to generally predict their occurrence. Baird (1998) concluded that leaving bends at or near the radius of curvature-width (R/W) ratio of 2 to 3 has lessened the need for man-made interventions. However, in general, the rate of meander migration, and hence bank erosion is maximized when the R/W values are between 2 and 3 (Nanson and Hickin, 1986; Harvey, 1988).

Given the extensive nature of the channelization of the river between Cochiti Reservoir and Elephant Butte Reservoir, and the degree of flood control that has been developed within the system, it is unlikely that there will be extensive lateral shift of the river in the future, especially where the bed of the channel is sand and the margins of the floodway are fixed with Kellner jack fields. The jacks have been very successful in preventing bank erosion where the river has a sand bed and the suspended-sediment concentrations are greater than about 4-5,000 mg/l. They have been much less successful where the suspended-sediment concentrations have been lower and the bed of the channel has been gravel (Baird, 1998). Rock revetments have been installed successfully in the gravel-bed reaches, but local scour has caused problems with some rock revetments in sand-bed reaches (Baird, 1998). Any type of bank protection that is emplaced before significant bed degradation occurs is likely to fail (Harvey and Watson, 1988). Therefore, where extensive channel degradation has occurred (between Angostura Diversion and Bernalillo, and downstream of San Acacia Diversion) it is likely that in-place bank protection will fail, thereby permitting bank erosion and channel migration. Further, in incised channels, bed degradation generally precedes and predisposes the channel banks to failure because the magnitude of the flood event contained within the channel increases, and the bank heights can exceed critical stability thresholds (Schumm et al., 1984; Harvey and Watson, 1988; Darby and Simon, 1999).

4.4. Changes in Bed Material

Changes in the bed material between 1970 and 1998 for locations between Cochiti Reservoir and San Acacia are summarized in Figure 3.41. It is apparent that between Cochiti Reservoir and Bernalillo, the bed of the channel is currently composed of gravel-sized material. The extent of the change that has occurred through time, as a result of the dam construction and water importation, is not clear in the reach between Cochiti Reservoir and Angostura Diversion.

Pre-Cochiti Reservoir reports on the bed material (Rittenhouse, 1944; Culbertson and Dawdy, 1964; Nordin and Beverage, 1965) indicate that the bed of the river was composed of gravels and cobbles over which a veneer of sand was present under low-flow conditions. Sampling bias in the pre-Cochiti period may well be responsible for the apparent extent of the coarsening. However, the limited amount of bed degradation downstream of the dam (Richard, 2001) tends to indicate that the bed material was coarse pre-dam. Without doubt the riverbed has coarsened between Angostura Diversion and Bernalillo (Figure 3.41), and it is currently composed of gravel (D_{50} of about 27 mm), and the greater extent of the degradation (Figure 4.7) is probably correlated with the finer bed material that was present in the pre-dam period (Culbertson and Dawdy, 1964).

At Albuquerque there has been a slight coarsening of the bed material since 1970. The D_{50} has increased from about 0.25 mm to 0.43 mm. This represents a change in bed material from fine to medium sand. Some gravel is currently present in the bed of the channel, but the available data indicate that it has been present since the early 1970s (Figure 3.37). At Bernardo there has been no appreciable change in the bed-material gradation (Figure 3.41). In 1970 the D_{50} was 0.17 mm, and in 1998 it was 0.2 mm, both of which fit into the fine sand category. At San Acacia, the D_{50} of the bed material has increased from 0.14 mm in 1970 to 0.26 mm in 1998 (Figure 3.41). However, the USGS data show an increase in the D_{84} values after about 1985 (Figure 3.39) when the flows were returned to the river. This suggests that there has been a winnowing effect as a result of the increased flows, and that the gravels were always present, but because the bed was sampled during low-flow periods the gravels were buried by sand. The Rio Salado is an obvious upstream source of the gravel.

Baird (2001) states that the Rio Puerco to San Acacia reach is now a partially gravel-bed reach, whereas it was historically sand. However, the MEI investigation conducted in 2001 did not substantiate the presence of gravels between the Rio Puerco and the Rio Salado. Similar conditions were reported by Baird in the San Acacia to Escondida reach of the river. He estimated that in this reach the bed will be entirely gravel in about 3 years. Unfortunately, data to support the above were not presented. The inference from Baird's statement is that there is a progressive change from sand to a gravel bed occurring, and that this is related to upstream changes in discharge and sediment supply. This reach of the river has the highest number of tributaries, and these tributaries drain the Joyita Uplift to the east (Figure 3.3), and every one of the tributaries is delivering gravel to the Rio Grande. It is not surprising, therefore, that gravel is present in the bed of the river at the tributary confluences. The D_{50} of the bed material, however, is likely to remain sand-size, as it has at the San Acacia gage (Figure 3.39), and downstream to San Antonio (Table 3.5).

4.5. Changes in Channel Capacity

Restoration goals for the Middle Rio Grande include reconnecting the main channel with the abandoned floodplain, among others (Baird, 2001). The river has been disconnected from its floodplain as a result of levee construction, channel degradation in some reaches, and reduced magnitude of flood peaks that inundate the floodplain relatively frequently, which is in the range of 2- to 5-year recurrence intervals, in non-perturbed systems (Williams, 1978).

To address the issue of changes in channel capacity over time, estimates of the average channel capacity were made for the 1962 conditions, and compared with observations of capacity that were reported by Crawford et al. (1993) for flows in 1992 and 1993. The photo-adjusted cross sections were used in local HEC-RAS models (normal-depth method) to determine channel capacity for selected cross sections in each of the identified channel reaches of the river between Cochiti and San Marcial. **Table 4.3** summarizes the 1962 channel capacity data by reach, and also provides information on the Pre-Cochiti flood frequencies associates with the channel capacity estimates.

Table 4.3. Summary of estimated 1962 channel capacities by reach, and associated pre-Cochiti flood recurrence intervals.

Reach	Range Line	Station (ft)	Channel Capacity (cfs)	Recurrence Interval (Gage, yrs)
1	170	825843	6,000	~1.5 (Cochiti)
2	227	796065	4,700	~1.5 (San Felipe)
3	350	733504	4,000	~1.2 (Albuquerque)
4a	800	505627	3,000	~1.0 (Albuquerque)
4b	1123	344662	3,000	~1.5 (Bernardo)
5	1200	304734	6,000	~1.3 (San Acacia)
6	1248	279954	3,000	~1.0 (San Acacia)
7	1464	168632	1,000	~ 1.0(San Acacia)
8	1633	82314	2,000	~1.0 (San Marcial)

The channel capacity data and their associated recurrence intervals indicate that while the magnitude of the channel capacity changed in the downstream direction, the recurrence interval was fairly constant (1.5 years) at least between Cochiti and San Acacia. Downstream of San Acacia, the recurrence interval and the magnitude of the channel capacity were both less, and this suggests that the channel was more aggraded (Happ, 1948). The capacity and associated recurrence interval data suggest that in the early 1960's the expected hydrologic relationship between the channel and the floodplain had not been significantly altered, at least where the river had not been channelized. However, the 1962 aerial photographs do indicate that significant lengths of the river, especially between Angostura Diversion and Bernardo, had been, or were in the process of being modified.

Crawford et al. (1993) report that discharges of 5,600 cfs in 1992 and 7,500 cfs in 1993 were fully contained within the channel between Cochiti Reservoir and Angostura Diversion. On the post-Cochiti flood-frequency curve a discharge of 7,500 cfs has a 5-year recurrence interval. At the least, this indicates that the combined effects of the documented channel bed lowering and the reduction in flood peaks have increased the recurrence interval of the channel filling discharge and reduced the frequency of overbank flows. Flood peaks of about 5,400 cfs in 1992 and 7,000 cfs in 1993 produced overbank flooding downstream of the Isleta Diversion to south of Belen (Crawford et al., 1993). This suggests that a 2-year event (about 5,400 cfs) will provide at least some overbank flooding in Reach 4a, and parts of Reach 4b. Observations of the recent (June 2001) release flows in the Albuquerque area suggest that a flow in excess of 5,000 cfs is required to cause some overbank flooding, which indicates that the channel capacities in the lower part of Reach 3 and in Reach 4a have increased slightly since 1962, but the recurrence-interval of the channel filling flow has also increased, and therefore, the overbank areas are flooded less frequently. Crawford et al. (1993) report that in 1992 the peak discharge of 5,400 cfs was retained in-channel between Bernardo and San Acacia, which suggests that the channel capacity in the lower part of Reach 4b has increased since 1962, when it was about 3,000 cfs (Table 4.3). It is not surprising that this flow was contained in Reach 5, because the channel capacity in 1962 was about 6,000 cfs.

From San Acacia to San Antonio (Reaches 6 and 7) all flows between about 3,900 cfs and 5,600 cfs in 1992 produced overbank flooding on about 10 percent of the floodplain (Crawford et al., 1993). However, the same flows produced overbank flows on about 90 percent of the floodplain between San Antonio and San Marcial in Reach 8. Similar levels of flooding were observed in 1993 when the peak discharge was on the order of 7,000 cfs. The capacity of the channel in Reach 6 is currently in question because of the possibility of channel degradation between 1992/1993 and the present (Baird, 2001), and it is possible that there has been some channel bed lowering in Reach 7 as well (Figure 4.7). Lowered bed elevations will increase the channel capacity, and reduce the frequency of overbank flooding. As discussed previously, the bed lowering in these reaches may have been an unintended consequence of returning flows to the river.

4.6. Riparian Vegetation

Riparian vegetation consists of the plant community that exists within a river channel and on the channel margins. Plant species that make up the riparian community tend to be adapted to the changing physical environment that characterizes a fluvial system. For example, Simon and Hupp (1988) demonstrated that specific geomorphic processes could be associated with riparian species in rapidly adjusting channels. The formation of fluvial landforms (bars, floodplains, and terraces) can be related to distinctive hydrogeomorphic processes (flow duration and flood frequency), which appear to be largely independent of vegetation (Hupp and Osterkamp, 1985). Once established, however, vegetation is an integral part of the fluvial system. Riparian vegetation has the potential to affect sediment deposition, channel stability, and the channel dynamics (Williams and Wolman, 1984), but the persistence of riparian species depends on the stability of the substrate (Petts, 1979; Lisle, 1988; Hupp, 1988).

Recruitment of riparian vegetation seedlings, especially cottonwoods, and ensuring their survival is generally associated with conditions where the establishment surfaces remain moist for at least the first week of growth and where shade is not excessive (Moss, 1938). Such establishment surfaces are most frequently associated with freshly deposited alluvium along streams, following high flows (Read, 1958; Fenner et al., 1984). On sandy alluvial substrates in dry regions, early establishment and growth of cottonwood seedlings may require water tables within 3 to 6 feet of the establishment surface (McBride and Strahan, 1984; Mahoney and Rood, 1992; Segelquist et al., 1993; Stromberg et al., 1996). Following seed germination and initial establishment, root growth allows young trees to survive gradual water table declines ranging between about 1 and 2 inches per day (Mahoney and Rood, 1992; Segelquist et al., 1993). Depth to the water table may increase as a result of subsequent floodplain accretion or channel incision (Everitt, 1968: Hereford, 1986), and cottonwood species have been observed at sites where depth to the water table is 20 - 30 feet (Robinson, 1958); however, mature cottonwoods are typically found in riparian settings where depth to the water table is less than 10 feet (Busch et al., 1992; Scott et al., 1997, 1999; Stromberg et al., 1996; Shafroth et al., 2000).

As can be seen from the above brief review of the literature, recruitment of native riparian vegetation depends to a great extent on the existence of an episodic disturbance regime in the fluvial system. It is obvious that the man-made interventions along the Middle Rio Grande have greatly reduced the occurrence of the driving forces, floods and sediment supply that are required for the establishment of riparian vegetation. Channelization and river stabilization projects have prevented lateral migration of the river and reworking of the floodplain that is required to form suitable substrate for plant colonization. Channel incision at some locations, as well as changes in the flood frequency have affected the relationships between the suitable substrate and the surface water and the groundwater table. As a result there has been little recruitment of native riparian species along the river.

In conjunction with the changed physical conditions that have tended to mitigate against the recruitment of native species, there has been the problem of introduction of exotic species such as salt cedar (tamarisk) and Russian olive that tend to thrive in the modified conditions that characterize the river at present. It is reported that the salt cedar was not prevalent along the Rio Grande until about 1926. Following the floods of 1929, the salt cedar spread rapidly. The distribution of the vegetation types between Cochiti and San Marcial was summarized by Crawford et al. (1993). Between Cochiti and San Marcial there are on the order of 20,300 acres of Cottonwood dominated timber and brush, the bulk of which (16,100 acres) is located between Cochiti and Bernardo. About 1,100 acres of Russian olive have been identified, and these are located primarily between Cochiti and San Acacia. About 17,800 acres of salt cedar are distributed along the river, but the bulk of the salt cedar (14,700 acres) is located between San Acacia and San Marcial. Reduced flood flows that less frequently disturb the system, when combined with increased base flows that maintain a higher water table have promoted the establishment and persistence of the exotic species (Johnson, 1994).

The very dense stands of salt cedar that flank the river in the San Acacia to San Marcial reach are probably related to the response of the river to reintroduction of flows after 1985. Extensive colonization of formerly bare sand bars is apparent on the 1972 and 1992 aerial photography, and this is related to the channel narrowing (Table 4.1). Although there are no supporting data, it is reasonable to assume that the general absence of flows in the river between 1959 and 1985, was probably conducive to establishment and growth of the salt cedar. Once the flows were returned to the channel, the very high hydraulic roughness created by the dense channel margin stands of salt cedar would most likely have forced more flow to remain in the channel, thereby increasing in-channel velocities. Higher velocities, coupled with the root-reinforced banks (Smith, 1976; MEI, 1996), would cause the channel bed to scour. The combined effects of channel scour, and vegetation-induced channel margin sediment deposition during flood flows, essentially increases the in-channel capacity, and create a negative feedback loop that increase the lateral stability of the channel and reduces the frequency of overbank flows.

4.7. Changes in River Morphology

The morphological characteristics of a significant proportion of the Middle Rio Grande has been modified by the changes in hydrology, sediment supply, channelization, bank protection, and installation of water supply and flood-control infrastructure (Plate A.1). Although much of the river was multi-channeled and braided in the 1917-1918 survey, today it is composed primarily of a single confined channel. Within the sand- bed reaches (3, 4a, 4b, 5, 6,7, and 8), the low-flow form of the single channel is still braided in most locations, especially downstream of the Isleta Diversion. The low-flow channel does not have a braided morphology where the channel is narrow in any of the reaches. Based on the 1997 aerial photography of the river, it appears that about 60 percent of the reach from Cochiti Reservoir to San Marcial has a low-flow braided morphology (Plate A.16). Between Angostura Diversion and Bernalillo the bed of the river has changed from sand to gravel (Plate A.9), but there is little evidence elsewhere along the river that there have been significant changes in the bed-material composition.

Bar morphology along the river is complex, and there is a hierarchy of bars present. In Reaches 1 and 2, the mid-channel bars tend to be relatively high elevation, coarse grained and vegetated, primarily with relatively large and well-established salt cedar and Russian olives (Plates A.2, A.3 and A.6). Except for areas where there are local tributary contributions of sediment, there are very few migrating, lower relief linguoid or braid bars that provide flow depth and velocity diversity (Germanoski, 1989), present within the channel (Plate A.5). In the upper part of Reach 3, between Angostura Diversion (Plate A.8) and Bernalillo, the mid-channel bars are relatively high, primarily composed of gravel, and are sparsely vegetated, which indicates that the bar sediments are being mobilized sufficiently frequently to prevent vegetation establishment (Plate A.10). Downstream of Bernalillo, the mid-channel bars are composed primarily of sand, but they are relatively high and they are well vegetated, primarily with exotic plant species (Plate A.11). Except where there is local tributary contribution of sediment, there are few migrating, low elevation braid bars (Plate A.12). In this Reach of the river, many of the mid-channel bars have become bank attached, and this has created a low sinuosity meandering planform (Plate A.13). Where the channel is wider, migrating braid bars are present in this Reach of the river (Plate A.14).

A major change in the in-channel morphology of the river occurs downstream of the Isleta Diversion at the head of Reach 4a. The number and frequency of migrating braid bars increases significantly (Plate A.15). There are very few higher elevation vegetated mid-channel bars in the Reach, which indicates that the bed of the channel is sufficiently mobilized to prevent vegetation establishment and encroachment in this Reach of the river (Plates A.16 and A.17). The intensely braided pattern persists throughout Reach 4b between Belen and Bernardo (Plates A.18 and A.19), but where the river narrows between the Rio Puerco confluence and the confluence with the Rio Salado there are few braid bars present in the channel (Plates A.20 and A.21). The Rio Salado is a major source of sediment, and between the confluence and San Acacia Diversion, there are numerous braid bars in the channel (Plate A.22). The braid bars are composed of both sand and gravel, which are introduced to the river by the Rio Salado (Plate A.23).

The channel of the Rio Grande has degraded over time downstream of the San Acacia diversion structure probably as a result of channelization downstream in the 1960s and as a result of some sediment trapping in the pool upstream of the diversion. The channel has narrowed and incised over time between the diversion structure and about the confluence with Arroyo Alamillo, located downstream of the San Lorenzo Settling Basin (Plate A.25). In this subreach there are few migrating braid bars, primarily because the deeper and more confined channel has a higher sediment transport capacity, but higher elevation vegetated bars are present in the reach. However, between Arroyo Alamillo and the upstream end of the channelized reach located about 1.5 miles upstream of the fan-induced (Arroyo de la Parida) constriction of the valley (Plate A.27), where the channel is wider, there are numerous actively migrating braid bars present in the channel (Plate A.26). Numerous tributaries are present in this reach of the river, and they are introducing both finer-grained (sand) and coarser (gravels) sediment to the Rio Grande (Plate A.28). Very few braid bars are present in the river in the narrow reach that is located both upstream and downstream of the bridge at Escondida (Plate A.29).

Between Escondida and San Antonio (Reach 7) where the channel is wider, there are numerous actively migrating low relief braid bars (Plate A.30). The number of braid bars is, therefore, related to the width of the channel because there is no doubt that the sediment supply to the reach from the tributaries is high, episodically. Numerous actively migrating braid bars are present in the wider channel segments in the upper part of Reach 8 between San Antonio and the middle of the Bosque del Apache NWR (Plate A.31). However, there are also a number of vegetated higher elevation bars in this reach of the river as well. Mechanical removal of the channel margin vegetation in the vicinity of the Bosque has effectively widened the river, and a significant number of braid bars are now present in the channel where few were present in 1992. Downstream of the Bosque the river is very narrow and few braid bars are present, except in locally wider reaches (Plate A.32). The channel narrowing process is probably assisted in this Reach by the presence of very thick deposits of silt and clay that appear to mantle all of the bars and promote colonization by vegetation (Plate A.33). Braid bars are present in the channel even in some of the narrower reaches because of the backfilling that is occurring upstream of Elephant Butte Reservoir (Plate A34). The backfilling has significantly reduced the ability to convey flows through the BNSF bridge at San Marcial (Plate A.35), and this lack of conveyance capacity is a major limitation to increasing the magnitude of flood flows to create overbank flows (Smith et al., 2001).

5. SUMMARY AND CONCLUSIONS

The general objectives of this study of the Middle Rio Grande from Cochiti Reservoir to Elephant Butte Reservoir were to (1) evaluate the historic and present characteristics of the river, (2) identify the natural and human-induced factors that control river characteristics, and (3) evaluate opinions that have been expressed by the USBR and others regarding the narrowing and incision of the river over the past century.

Specific objectives of the investigation included:

1. Identification of geomorphic and sediment data that will be necessary to develop a predictive tool(s) that relates river flow and physical characteristics of the river.

2. Assembly and evaluation of the existing data, and review and analysis of studies conducted by others.

3. Evaluation of the geomorphology of the river immediately downstream of each of the diversion dams (Angostura, Isleta, and San Acacia) to provide a basis for evaluating proposed restoration projects by the U.S. Bureau of Reclamation (USBR).

4. Qualitative evaluation of how currently proposed habitat restoration activities, if implemented, would affect river efficiency (i.e., ability to convey flows downstream with minimal losses through seepage, evaporation and evapotranspiration).

5. Qualitative evaluation of where natural overbank flooding was possible immediately after closure of Cochiti Dam in 1973, and under present conditions.

6. Preliminary identification of where it might be possible to modify the floodplain to allow short-term inundation of the floodplain.

5.1. Summary

The Middle Rio Grande has been affected by human interventions since the 1800s, when abstractions for irrigation in the San Luis Basin in Colorado, reduced the natural flows in the river by 40 to 60 percent (National Resources Commission, 1938). By about 1880 a maximum of about 125,000 acres of land was under cultivation in the Middle Rio Grande Valley. This leads to both increased water abstraction from the river and removal of riparian vegetation (Crawford et al., 1993). The area of irrigated lands was sharply reduced by 1926 to about 45,000 acres, with an attendant reduction in the amount of water removed from the river. Sediment loads to the river were elevated in the late 1800s by arroyo incision (Happ, 1948). Major increases in sediment load occurred downstream of the Rio Puerco confluence as a result of trenching of the Rio Puerco (Rittenhouse, 1944; Happ, 1948; Elliott, 1979). Bryan and Post (1927) estimated that between 1887 and 1928 about 394,882 acre-feet (33 M tons) of sediment was delivered to the Rio Grande by the Rio Puerco. The earliest detailed information available on the planform characteristics of the river was the 1917-1918 survey, but by the time this survey was conducted, the hydrology and sedimentology had changed considerably, and there is uncertainty whether the form of the river represented an equilibrium form.

The river between Cochiti Reservoir and San Marcial was subdivided into nine reaches on the basis of natural geomorphic and geologic controls on sediment storage in the valley (Table 2.1). The reach between the Isleta Diversion and Canada Ancha was further subdivided into two subreaches because of the documented effects of the active Belen-Socorro Uplift that has, and continues to, affect the slope of the river. Reach 4a between Isleta Diversion and Belen is upstream of the influence of the uplift: whereas, Reach 4b is directly affected by the uplift. When the individual reaches are plotted on the Lane (1957) diagram using the 1917-1918 slopes and the mean annual discharge for the pre-Cochiti and pre-water importation period, all of the reaches plot in the transition zone between braided and meandering (Figure 2.11). The river in the two upstream reaches (Cochiti to Angostura Diversion) had a multiple-channel anastomosed planform. The remainder of the reaches were braided, but there were, as expected from the plotting positions on Figure 2.11, meandering characteristics in most of the reaches (Figure 2.12). Channel width data developed from the 1917-1918 survey showed a general trend of increasing channel width in the downstream direction, but the variance in width also increased in the downstream direction (Figure 4.3). There is little doubt that the river was episodically modified by relatively infrequent large floods. In the period between the large floods, there was a more systematic development of meandering characteristics, but during large floods, the system was avulsive and the bends, which constituted sediment storage zones, were abandoned (Happ, 1948). A series of large floods in the late 1920s, 1930s and early 1940s caused a significant number of channel avulsions, considerable overbank flooding, and sediment deposition on the valley floor. The floods of the 1920s, 1930s and 1940s led to the development of the flood-control system, as well as the flow conveyance system (Figure 3.81).

In order to improve efficiency of water conveyance to Elephant Butte Reservoir, the Low Flow Conveyance Channel (LFCC) was built with a capacity of about 2,000 cfs. From 1959 to 1985 virtually all the flows were conveyed in the LFCC, and the river for all intents and purposes was abandoned and referred to as the floodway. Since 1985, the LFCC has not been used to convey flows, and the flows have been returned to the river. Channelization of the river was extensive, and by 1962, a considerable portion of the river had been narrowed and stabilized with jack fields (Table 3.13). Additional channelization occurred between 1962 and 1972 , and between 1972 and 1992 in Reach 1 (Cochiti to San Felipe, Table 3.14). Between 1917-1918 and 1972, there was, as a result of the channelization project, a major reduction in channel width in all reaches of the river (Table 4.1). Reach-averaged channel widths in 1972 were between 24 and 52 percent of those in 1917 to 1918.

Major changes in the hydrology and sedimentology of the system occurred in the early and mid 1970s when the flood-control reservoirs were constructed on the Rio Grande (Cochiti Reservoir) and Galisteo Creek, and the San Juan-Chama water importation project (on average 96,600 acre-feet per year) came on line. Jemez Reservoir was constructed in the early 1950s. An additional 69,000 acre-feet of water was added to the river as a result of wastewater discharge from the City of Albuquerque. The combined effects of these projects were (1) reduced flood peaks (Table 3.1), (2) additional flow volumes that had significant effects on the distribution of flows, especially downstream of Albuquerque (Table 3.2), (3) reduction in the sediment delivery to the upper reaches (Table 3.7), and (4) changes in the bed-material sediment gradations (Table 3.4).

The analysis of sediment-transport trends in the pre- and post-Cochiti Reservoir periods indicate that the dams have had a significant impact on the sediment-transport characteristics of the Middle Rio Grande. The effects of Cochiti Dam are evident in the suspended (Figures 3.43 through 3.49) and bed-material rating curves (Figures 3.50 through 3.55) that were developed for the pre- and post-dam periods that show an overall reduction in the amount of sediment being transported in the post-dam period. However, the data also show that the impacts of the dam are greatly reduced in the downstream direction. The average annual suspended-sediment concentrations (Table 3.7) and the double mass curves (Figures 3.56 through 3.62) all show a reduction in sediment transport in the post-dam period as well. The effective discharge estimates based on both the bed-material load (Table 3.8) and suspended load (Table 3.9) show a reduction in the range of flows that transport the most sediment, but the effective discharges are not related to bankfull or channel-forming discharges.

Statistical analysis (t-tests of the means) of the mean channel widths for the individual reaches between 1972 and 1992 indicated that only in Reach 6 (San Acacia to Escondida) was the mean width statistically different in 1992. The width reduction is probably due to a number of factors, including the absence of flows between 1959 and 1985, which allowed the salt cedar to colonize the stable substrate. The lack of statistically significant differences in the other reaches is due to the large variance in widths within the individual reaches (Table 4.1). In fact, review of the width data between 1972 and 1992 showed that there were numerous locations where the channel widened, as well as locations where there was narrowing (Figure 4.2). Baird (2001) has hypothesized that the there has been general channel narrowing due to the changes in hydrology and sediment supply caused by the upstream dams, but with the exception of Reach 6, the hypothesized narrowing trend does not appear to exist. There appear to be two problems with Baird's interpretation of the data. First, the baseline that he uses is 1962, which predates the hydrologic and sedimentologic changes of the 1970s, and therefore, confounds any interpretation of the changes. Second, there is an implicit assumption that the river was adjusted to the channelization, and that the river was no longer responding to the imposed changes in the post-1962 period.

Changes in thalweg (Figure 4.6) and mean bed elevation (Figure 4.7) have been determined for various reaches and between time periods. Because of the ability of thalweg elevations to change significantly between flow events, the mean bed elevation data provide a better indicator of trends. There is no doubt that there has been degradation of the channel between Cochiti Reservoir and Angostura Diversion between 1973 and 1995, but on average, the change in mean bed elevation has been less than 3 feet, and in many locations, it has been less than a foot, probably because the bed is armored. Between the Angostura Diversion and Bernalillo between 1973 and 1998, the reduction in mean bed elevation has been as much as 5 feet, but on average, it appears to have been more on the order of 3 to 4 feet. Between Isleta and about Bernardo, there has been about 2 feet of average bed elevation decline, but interpretation of the cause is uncertain because of the confounded period of record (1962-1998). It is possible that the decline is due to the increased duration of flows in the 800 to 900 cfs range (Table 3.2). Downstream of Bernardo to the Rio Salado confluence, reductions in mean bed elevation of up to 4 feet were recorded in the 1962-1998 period. The reduction in bed elevation appears to be correlated with channel narrowing. There has been up to 12 feet of bed lowering immediately downstream of the San Acacia Diversion in the period from 1962 to 1998, but the values range from 6 to 12 feet in the reach. The degradation in the upper part of the reach appears to be mainly related to the channelization project in the 1960s, although increased flows in the post-1970s period may also be responsible for the observed degradation. The combined effects of greater flow volumes in a narrower channel with very high hydraulic roughness on the margins, due to the dense salt cedar, may be responsible for the approximately 2 feet of average bed elevation reduction from Escondida to the Bosque del Apache NWR since 1987 (Figure 4.7). The backwater effects of Elephant Butte Reservoir are obviously responsible for the aggradation observed downstream of the Bosque (Figure 4.7).

Closure of Cochiti Dam as well as Jemez Reservoir and Galisteo Dam has significantly reduced the supply of sediment to the upper reaches. Based on Rittenhouse (1944) and Happ (1948), it appears that the dams eliminated about 35 percent of the upstream sediment supply (Table 3.10). There is no doubt that the bed of the river has coarsened between Cochiti Reservoir and Angostura Diversion, but the extent of the coarsening is unclear. Prior to dam closure the bed of the channel was described as being composed of gravel- and cobble-sized material

(Rittenhouse, 1944; Culbertson and Dawdy, 1964; Nordin and Beverage, 1965). The presence of the coarse sediment has reduced the amount of channel degradation downstream of the dam (Richard, 2001). Between Angostura Diversion and Bernalillo the bed has definitely coarsened in the post-dam period, and it is now a gravel-bed reach (Figure 3.41). Farther downstream, however, the river still has a sand bed, even though there may have been some coarsening of the bed material (Figure 3.41, Table 3.4). Gravels in the bed of the channel downstream of San Acacia are being supplied by the numerous tributaries in the reach.

The very dense stands of salt cedar that flank the river in the San Acacia to San Marcial reach are probably related to the response of the river to reintroduction of flows after 1985. Extensive colonization of formerly bare sand bars is apparent on the 1972 and 1992 aerial photography, and this is related to the channel narrowing (Table 4.1). Although there are no supporting data, it is reasonable to assume that the general absence of flows in the river between 1959 and 1985 was probably conducive to establishment and growth of the salt cedar. Once the flows were returned to the channel, the very high hydraulic roughness created by the dense channel margin stands of salt cedar would most likely have forced more flow to remain in the channel, thereby increasing in-channel velocities. Higher velocities, coupled with the root-reinforced banks (Smith, 1976; MEI, 1996), would cause the channel bed to scour. The combined effects of channel scour, and vegetation-induced channel margin sediment deposition during flood flows, essentially increases the in-channel capacity, and creates a negative feedback loop that increases the lateral stability of the channel and reduces the frequency of overbank flows.

The morphological characteristics of a significant proportion of the Middle Rio Grande have been modified by the changes in hydrology, sediment supply, channelization, bank protection, and installation of water supply and flood-control infrastructure. Although much of the river was multi-channeled and braided during the 1917-1918 survey, today it is composed primarily of a single confined channel. Within the sand-bed reaches (3, 4a, 4b, 5, 6,7, 8), the low-flow form of the single channel is still braided in most locations, especially downstream of the Isleta Diversion. The low-flow channel does not have a braided morphology where the channel is narrow in any of the reaches. Based on the 1997 aerial photography of the river, it appears that about 60 percent of the reach from Cochiti Reservoir to San Marcial has a low-flow braided morphology. Between Angostura Diversion and Bernalillo, the bed of the river has changed from sand to gravel, but there is little evidence elsewhere along the river that there have been significant changes in the bed material.

5.2. Conclusions

Based on the data assembled and evaluated during this geomorphic and sediment investigation of the Middle Rio Grande between Cochiti Reservoir and Elephant Butte Reservoir, the following general conclusions can be made about changes in hydrology and sediment supply to the Rio Grande:

1. The hydrology of the Middle Rio Grande has been significantly changed though time as a result of flow importation, wastewater discharge, abstraction for irrigation and returns from irrigation flows, and the construction of water supply and flood-control reservoirs. Importation of flows via the San Juan-Chama project has added about 97,000 acre-feet of flow to the basin annually since 1971, of which about 54,000 acre-feet is delivered to the Otowi gage. The City of Albuquerque wastewater delivery to the river is on the order of 60,000 acre-feet annually. The additional water has had a significant effect on the amount of water in the Rio Grande downstream of Albuquerque where median flows (50^{th} percentile) on the mean daily flow-duration curves have increased from about 0 to about 1,000 cfs at the Bernardo gage. The flood-control reservoirs have reduced the

magnitude of flood peaks significantly, and there have been no significant floods on the river since the 1970s. At the Cochiti gage, there has been a 30 percent reduction in the 2-year flood and about a 55 percent reduction in the magnitude of the 100-year flood. Similar reductions apply at the other gages downstream of Cochiti.

2. The flood- and sediment-control reservoirs have had a major effect on sediment transport downstream of Cochiti Dam. Suspended-sediment loads and bed-material loads are both lower then they were in the pre-dam period, but the effects of the dams diminish in the downstream direction. However, other watershed factors appear to be the cause of some of the reduced sediment loads because sediment loads have also diminished at the Otowi gage, which is located upstream of Cochiti Dam. Watershed factors could include improved land use in the basin as well as storage of sediment in many of the arroyos that incised in the 1800s. Below the Rio Puerco confluence, tributaries and in-channel sources of sediment significantly reduce the effects of the upstream dams.

Changes in the hydrology and sediment supply to the Rio Grande following construction of the dams in the 1970s have been used to explain changes in channel morphology and planform, channel narrowing, channel incision, changes in bed-material composition and channel armoring (Carter, 1955; Culbertson and Dawdy, 1964; Dewey et al., 1979; Graf, 1994; Lagasse, 1994; Baird, 1989, 2001). Because of the length of time over which changes have been ongoing, as well as the wide range of physical changes that have been imposed on the system, there is a very real possibility for confounding of cause and effect, and therefore, interpretations of cause and effect should be regarded with caution. Review of published and unpublished conclusions regarding the existing and present day geomorphology and sedimentology of the river, and analysis of the data presented in this report, allow the following to be concluded regarding the changes in the Rio Grande:

1. Because of upstream water abstraction in the1880s, irrigation demands in the Middle Rio Grande in the same time period, and the increase in sediment supply due to the incision of many arroyos, including the Rio Puerco, as well as changes in land use, the planform and other morphologic characteristics of the Rio Grande may not have been in equilibrium with the flows and sediment supply at the time of the river's 1917-1918 survey. Therefore, the 1917-1918 survey may not be a robust baseline with which to compare the river's present day morphology and dynamics.

2. Based on the Lane (1957) discriminate functions between braided and meandering channels, all of the nine identified reaches plot within the transition zone between braided and meandering channels. Therefore, it is not surprising that the river has both braided and meandering characteristics. Approximately 60 percent of the river between Cochiti and Elephant Butte Reservoir still has a braided planform under low-flow conditions. From Cochiti to about Isleta, bars have become bank-attached and stabilized with primarily non-native plant species. As a result of the stabilization of the bars, and the significant reduction in the magnitude of the peak flows due to the flood-control dams, the river is developing a low-sinuosity, meandering planform.

3. Although the reach-averaged mean channel widths increased in the downstream direction in 1917-1918, the variability also increased, most probably as a result of the increase in sediment delivery downstream of the Rio Puerco confluence where because of geologic controls, a significant number of tributaries historically, and presently, contributed sediment to the Rio Grande.

4. Between 1917-1918 and 1972, the mean widths of the channel in the nine reaches was reduced to 24 to 52 percent of the 1917-1918 widths depending on the reach. Channel narrowing commenced before the closure of Cochiti Dam. The majority of the decline in width was due to the channelization project that was designed to increase the efficiency of flow conveyance.

5. Except for Reach 6 (San Acacia to Escondida), the changes in mean width for the individual reaches between 1972 and 1992 are not statistically significant, and therefore, there is little evidence to indicate that the post-Cochiti hydrologic and sedimentologic changes have resulted in channel narrowing. The Reach 6 narrowing is probably related to the combined effects of channel incision as a result primarily of channelization, and a lack of flows between 1959 and 1985 that encouraged the encroachment by salt cedar.

6. Construction of the dams has lead to about 3 feet of general bed degradation between Cochiti Reservoir and Angostura Diversion. The presence of gravels and cobbles in the bed in this reach prior to dam closure has lead to bed-material armoring that has limited the amount of degradation. In contrast, there has been as much as 5 feet of general bed lowering between Angostura Diversion and Bernalillo in the post-dam period, because the bed was not composed of gravels and cobbles prior to dam closure. The previously sand-bed reach now has a gravel bed. Approximately 2 feet of channel degradation has occurred at the Albuquerque gage.

7. There has been about 2 feet of average bed lowering between 1962 and 1998 downstream of Isleta. However, it is not clear whether this is related to channelization, or changes in the hydrology. Significant increases in the flows in the 600 to 800 cfs range as a result of flow importation and metropolitan wastewater disposal, are likely to have caused a similar change in the bed of the river. Between Bernardo and the Rio Salado confluence, there has been about 4 feet of general bed lowering in the 1962 to 1998 period. The degradation appears to be related to channel narrowing.

8. Up to 12 feet of channel degradation has occurred immediately downstream of the San Acacia Diversion in the 1962 to 1998 period. The most likely causes of the degradation are the 1960s channelization, and the increased volumes of flow that have been introduced to the river since the flows were returned to the river in 1985 from the LFCC. Downstream of Escondida, the approximately 2 feet of bed lowering since 1987 is probably an unintended consequence of returning flows to the river. A narrowed river channel with very high hydraulic roughness on the margins due to dense salt cedar stands is likely to scour as more flow is forced into the channel.

9. Although there has been some coarsening of the bed material downstream of Bernalillo in the post-dam period, the bed material is still sand. The presence of some gravels in the bed downstream of San Acacia is probably due to flushing of gravels introduced to the river from the Rio Salado from the San Acacia Diversion structure. The numerous east-side tributary arroyos are all supplying gravels to the river, and therefore, the presence of gravels in the bed of the river near the tributaries is not a sign of upstream dam-induced channel coarsening. Sampling of the riverbed in 2001 between San Acacia and San Antonio did not reveal any general coarsening trends in the bed material.

10. The changed morphology of the Rio Grande, due to the channelization project, has converted what was historically a multi-channeled multi-thalweg river into a single channel. Braid bars are only found in wider reaches of the river. Mechanical widening

of the narrow reaches is likely to provide increased areas of braid bars under the present hydrologic and sediment regime.

11. The lack of flood flows and the attendant absence of a disturbance regime, as well as the increased base flows tend to mitigate against the establishment of native riparian species, and to promote the continued establishment of the non-native exotic species such as salt cedar and Russian olive.

12. Lateral migration of the river has been essentially prevented by the extensive use of jack fields and other forms of bank protection. This has eliminated a source of sediment for the river and may have contributed to some of the channel incision. Within the channelized reaches, planform change is due to stabilization of bank-attached bars by vegetation between the channel-bounding jack fields. Localized areas of bank erosion do occur along the river, but they are not sufficient to cause a major change in the planform of the river. The roots of extensive areas of non-native vegetation have effectively narrowed and stabilized much of the river, especially downstream of San Acacia where the river has not incised below the rooting depth of the plants.

13. Upstream of Isleta, very little if any overbank flooding occurs at a discharge of 5,700 cfs, which has a recurrence interval of about 2 years. Between Isleta and Belen, it appears that overbank flows can be generated at flows on the order of 5,700 cfs. Between Bernardo and San Acacia, the channel capacity is higher than 5,700 cfs and therefore, the frequency of overbank flows is lower. Between San Acacia and San Antonio flows up to about 5,700 cfs can produce some overbank flooding. Downstream of San Antonio, extensive overbank flooding is caused by flows in the same range.

14. Effective discharge computations using both the bed-material load and the suspended-sediment load indicate that the present morphology of the river is not in equilibrium with the discharge and sediment regimes. With the exception of the value computed with the bed-material load at the Albuquerque gage, the computed effective discharge value for each of the gages is equaled or exceeded between 40 and 50 percent of the time on the mean daily flow-duration curve. Therefore, prediction of future changes in channel morphology in response to changes in discharges and sediment loads is problematic.

5.3. Recommendations

Based on the results of this investigation, it is apparent that there are uncertainties regarding the geomorphology and sedimentology of the Middle Rio Grande. Until these uncertainties, that are generally based on a lack of specific data, are resolved, it will be difficult to evaluate the potential for restoration of the river. Specific recommendations are as follows:

1. Develop a sediment budget for the river that takes into account the episodic nature of the tributary sediment contributions.

2. Develop at least one-dimensional hydraulic models of the river that will provide quantitative and reach-specific estimates of channel capacity.

3. Develop a sediment-transport model that can be used to determine the current vertical stability of the channel in the individual reaches.

4. Use the sediment-transport model to evaluate the hydraulic and morphologic consequences of any potential river restoration alternatives.

5. Evaluate the role of fine-grained sediment that is primarily delivered by the tributaries, on vegetation encroachment as well as braid-bar stabilization that can lead to changes in river morphology.

6. Evaluate the current morphology of the channel based on more recent surveys than were available at the time of this investigation.

7. Evaluate the hydraulic and morphologic effects of very high channel margin hydraulic roughness provided by invasive non-native plant species, and their potential impacts on channel capacity and frequency of overbank flows.

8. Evaluate the effects of existing and future channel degradation on existing in-channel and channel-margin infrastructure.

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EXECUTIVE SUMMARY

The objectives of this investigation of the geomorphology and sedimentology of the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir were to: (1) evaluate the historic and present characteristics of the river, (2) identify the natural and human-induced factors that control the present day river characteristics, and (3) evaluate existing opinions regarding the causes of channel narrowing, armoring of the bed and incision of the river. The study was based on a review of published and unpublished literature and data, and limited aerial and field reconnaissance. For the purposes of this investigation the Middle Rio Grande was subdivided into 9 reaches. Changes in the hydrology and sediment supply to the Rio Grande following construction of the flood and sediment control dams in the 1970s have been used to explain changes in channel morphology, such as planform change, channel narrowing, channel incision, and changes in bed material composition and channel armoring (Crawford et al., 1993; Graf, 1994; Lagasse, 1994; Baird, 1989, 2001). However, because of the length of time over which changes have been on going (since at least the 1800's), as well as the wide range of physical changes that have been imposed on the system, there is a very real possibility for confusion regarding cause(s) and effect(s).

The Middle Rio Grande has been significantly affected by human interventions since the 1800s, when abstractions for irrigation in the San Luis Basin in Colorado, reduced the natural flows in the river by 40 to 60 percent (National Resources Commission, 1938). Sediment loads to the river were elevated in the late 1800's by arroyo incision and changes in land use in the basin (Happ, 1948). Major increases in sediment load occurred downstream of the Rio Puerco confluence as a result of incision of the Rio Puerco (Rittenhouse, 1944; Happ, 1948; Elliott, 1979). By about 1880, 125,000 acres of land was under cultivation in the Middle Rio Grande Valley, and this led to both increased water abstraction from the river, and removal of riparian vegetation (Crawford et al., 1993). The earliest detailed information available on the planform characteristics of the river was a 1917-1918 survey (U.S. Reclamation Service, 1922), but by the time this survey was conducted, the hydrology and sediment supply to the river had changed considerably, and there is uncertainty whether the morphology and dynamics of the river were in equilibrium.

By 1935, the Middle Rio Grande Conservancy District (MRGCD) had constructed El Vado Dam on the Rio Chama, as well as diversion dams at Cochiti, Angostura, Isleta, and San Acacia. MRGCD also constructed more than 180 miles of riverside drains and 160 miles of interior drains that improved conditions for irrigation. As part of the drain project, linear piles of spoils were placed between the riverside drains and the river. These piles followed the existing river planform and eventually became levees that were used for flood control (Graf, 1994). The design consisted of a floodway that averaged 1,500 feet wide between 8-foot levees (Lagasse, 1980). The levees were built to withstand a design discharge of 40,000 cfs and the levees, near the City of Albuquerque, were raised to pass a design flow of 75,000 cfs (Woodson and Martin, 1963). High flows in 1941 and 1942 with discharges over 21,000 cfs caused severe damage in the valley. As much as 50,000 acres were inundated as the levees were breached in 27 different locations (Scurlock, 1998; Graf, 1994). After these devastating floods the USBR and the Army Corps of Engineers (COE) devised the Rio Grande Comprehensive Plan (Lagasse, 1980). The Comprehensive Plan involved a system of reservoirs on the Rio Grande (Cochiti, 1973) and its tributaries (Jemez 1954; Abiquiu 1963; Galisteo 1970), as well as rehabilitation of the floodway constructed by MRGCD (Woodson and Martin, 1963).

In order to improve efficiency of water conveyance to Elephant Butte Reservoir, the Low Flow Conveyance Channel (LFCC) that extended from San Acacia to the reservoir was built with a capacity of about 2,000 cfs. From 1959 to 1985 virtually all the flows were conveyed in the

LFCC, and the river for all intents and purposes was abandoned, and it was referred to as the floodway. Since 1985 the flows have been returned to the river.

The present day hydrology of the Middle Rio Grande has been significantly changed due to flow importation, wastewater discharge, abstraction for irrigation and returns from irrigation flows, and the construction of water supply and flood-control reservoirs. Importation of flows via the San Juan-Chama project has added about 97,000 acre-feet of flow to the basin annually since 1971, of which about 54,000 acre-feet is delivered to the Otowi gage (Annual Rio Grande Compact Accounting Report). The City of Albuquerque wastewater delivery to the river is on the order of 60,000 acre-feet annually. These changes have had a significant effect on the amount of water in the Rio Grande downstream of Albuquerque where median flows (50th percentile) on the mean daily flow duration curves for the Bernardo, San Acacia and San Marcial gages have increased significantly. The flood-control reservoirs have reduced the magnitude of flood peaks significantly, and there have been no significant floods on the river since the 1970s. At the Cochiti gage there has been a 30 percent reduction in the magnitude of the 2-year flood, and about a 55 percent reduction in the magnitude of the 100-year flood. Similar reductions apply at the other gages downstream of Cochiti.

The flood- and sediment-control reservoirs have had a major effect on sediment transport downstream of Cochiti Dam. Suspended-sediment loads and bed-material loads are both lower than they were in the pre-Cochiti Dam period, but the effects of the dams diminish in the downstream direction because of tributary sediment delivery and in-channel sources of sediment. Average annual suspended-sediment concentrations have been reduced by about 99 percent at the Cochiti gage, but by only 70 percent at the San Marcial gage. However, other watershed factors appear to be the cause of some of the reduced sediment loads, because average annual suspended-sediment concentrations have also diminished by about 55 percent at the Otowi gage in the same time period. Watershed factors could include improved land use in the basin, as well as storage of sediment in many of the arroyos that initially incised in the 1800s and then widened sufficiently to permit sediment deposition (Schumm et al., 1994).

Review of published and unpublished literature and data regarding the historical and present day geomorphology and sedimentology of the river, and analysis of the data presented in this report, allow the following to be concluded regarding the changes in the Middle Rio Grande:

- Approximately 60 percent of the river between Cochiti and Elephant Butte Reservoir still has a braided planform under low-flow conditions. From Cochiti to about Isleta, bars have become bank attached and stabilized with primarily non-native plant species. As a result of the stabilization of the bars, and the significant reduction in the magnitude of the peak flows due to the flood-control dams, the river is developing a low sinuosity meandering planform.

- Between 1917-1918 and 1972, the mean widths of the channel in the nine reaches was reduced to 24 to 52 percent of the 1917-1918 widths depending on the reach. Channel narrowing commenced before the closure of Cochiti Dam. The majority of the decline in width was due to the channelization project that was designed to increase the efficiency of flow conveyance.

- Except for the reach between San Acacia and Escondida (Reach 6), the changes in mean width between 1972 and 1992 for the other identified reaches are not statistically significant, and therefore, there is little evidence to indicate that the post-Cochiti hydrologic and sedimentologic changes have resulted in channel narrowing. The Reach 6 narrowing is probably related to the combined effects of channel incision as a result primarily of channelization, and a lack of flows between 1959 and 1985 that encouraged encroachment into the channel by salt cedar.

- Construction of the dams has led to about 3 feet of general bed degradation between Cochiti Reservoir and Angostura Diversion. The presence of gravels and cobbles in the bed in this reach prior to dam closure has led to bed-material armoring that has limited the amount of degradation. In contrast, there has been as much as 5 feet of general bed lowering between Angostura Diversion and Bernalillo in the post-dam period, because the bed was not composed of gravels and cobbles prior to dam closure. The previously sand-bed reach now has a gravel bed. Approximately 2 feet of channel degradation has occurred at the Albuquerque gage, but there has not been a significant change in the bed material.

- There has been about 2 feet of average bed lowering between 1962 and 1998 downstream of Isleta. However, it is not clear whether this is related to channelization or changes in the hydrology. Significant increases in the flows in the 600 to 800 cfs range, as a result of flow importation and metropolitan wastewater disposal are likely to have caused an incision of a similar magnitude. Between Bernardo and the Rio Salado confluence, there has been about 4 feet of general bed lowering in the 1962 to 1998 period. The degradation appears to be related to channel narrowing.

- Up to 12 feet of channel degradation has occurred immediately downstream of the San Acacia Diversion in the 1962 to 1998 period. The most likely causes of the degradation are the 1960s channelization and the increased volumes of flow that have been introduced to the river since the flows were returned to the river in 1985 from the LFCC. Downstream of Escondida, the approximately 2 feet of bed lowering since 1987 is probably an unintended consequence of returning flows to the river. A narrowed river channel with very high hydraulic roughness on the margins due to dense salt cedar stands is likely to scour as more flow is forced into the channel.

- Although there has been some coarsening of the bed material downstream of Bernalillo in the post-dam period, the bed material is still sand. The presence of some gravels in the bed downstream of San Acacia is probably due to flushing from the San Acacia Diversion structure of gravels introduced to the river from the Rio Salado. The numerous east-side tributary arroyos are all supplying gravels to the river, and therefore, the presence of gravels in the bed of the river near the tributaries is not a sign of upstream dam-induced channel coarsening. Sampling of the riverbed in 2001 between San Acacia and San Antonio did not reveal any general coarsening trends in the bed material.

- The changed morphology of the Rio Grande, due to the channelization project, has converted what was historically a multi-channeled multi-thalweg river into a single channel. Braid bars are only found in wider reaches of the river. Mechanical widening of the narrow reaches is likely to provide increased areas of braid bars under the present hydrologic and sediment regime.

- The lack of flood flows and the attendant absence of a disturbance regime, as well as the increased base flows tend to mitigate against the establishment of native riparian species, and to promote the continued establishment of the non-native exotic species such as salt cedar and Russian olive.

- Lateral migration of the river has been essentially prevented by the extensive use of jack fields and other forms of bank protection. This has eliminated a source of sediment for the river and may have contributed to some of the channel incision. Within the channelized reaches, planform change is due to stabilization of bank-attached bars by vegetation between the channel-bounding jack fields. Localized areas of bank erosion do occur along the river, but they are not sufficient to cause a major change in planform of the river. Extensive areas of non-native vegetation have effectively narrowed and stabilized much of the river, especially downstream of San Acacia where the river has not incised below the rooting depth of the plants.

- Upstream of Isleta, very little if any overbank flooding occurs at a discharge of 5,700 cfs, which has a recurrence interval of about 2 years. Between Isleta and Belen, it appears that overbank flows can be generated at flows on the order of 5,700 cfs. Between Bernardo and San Acacia, the channel capacity is higher than 5,700 cfs and therefore, the frequency of overbank flows is lower. Between San Acacia and San Antonio, flows up to about 5,700 cfs can produce some overbank flooding. Downstream of San Antonio extensive overbank flooding is caused by flows in the same range.

- Effective discharge computations using both the bed-material load and the suspended-sediment load indicate that the present morphology of the river is not in equilibrium with the discharge and sediment regimes. With the exception of the value computed with the bed-material load at the Albuquerque gage, the computed effective discharge value for each of the gages is equaled or exceeded between 40 and 50 percent of the time on the mean daily flow-duration curve. Therefore, prediction of future changes in channel morphology in response to changes in discharges and sediment loads is problematic.