GEO-17
~~523 H-4~~
duplicate.
Admin Review

Upper Rio Grande Water Operations EIS

Middle Rio Grande Planform Characterization and Analysis

Report Prepared by:

Paula W. Makar, Hydraulic Engineer
Sedimentation and River Hydraulics Group

Travis R. Bauer, Hydraulic Engineer
Sedimentation and River Hydraulics Group

Report Peer Reviewed by:

Drew C. Baird, Ph.D., P.E., Hydraulic Engineer
Sedimentation and River Hydraulics Group

June 2004

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center, Denver, Colorado

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name: Upper Rio Grande Water Operations EIS
WOID: AB177
Document: Middle Rio Grande Planform Characterization and Analysis
Document Date: June 2004
Date Transmitted to Client: June 15, 2004
Team Leader: Paula W. Makar
Water Resources Division Chief: Jim Pierce
Document Author(s)/Preparer(s): Paula W. Makar, Travis R. Bauer
Peer Reviewer: Drew C. Baird; Ph.D, P.E.

Review Certification

Peer Reviewer: I have reviewed the document listed above and believe it to be in accordance with project requirements, standards of the profession and Reclamation policy.

Reviewer_____ Date reviewed_____

Preparer: I have discussed the document listed above, review requirements, and believe that this review is completed, and the document will meet the requirements of the project.

Team Member_____ Date signed_____

Team Member_____ Date signed_____

DEPARTMENT OF THE INTERIOR MISSION STATEMENT

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitment to island communities.

BUREAU OF RECLAMATION MISSION STATMENT

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public

Table of Contents

PEER REVIEW DOCUMENTATION ..... **ii**
1. Introduction and Background **1**
2. River Morphological Influences **2**
3. River Operations Reaches **5**
4. Methods **7**
4.1 GIS Database 7
4.2 Geomorphic categories 9
4.3 Active Channel Width 9
4.4 Floodplain Width 9
4.5 Island Area 12
4.6 Sinuosity 13
5. Results and Discussion **14**
5.1 Active Channel Width 14
5.2 Floodplain width 15
5.3 Island area 16
5.4 Sinuosity 17
5.5 Width Analysis 19
6. Conclusions **29**
7. References **30**
APPPENDIX A Width Variability of Subreaches **33**

List of Figures

Figure 1. Upper Rio Grande basin and study reach 1
Figure 2. Timeline of significant events 3
Figure 3. Comparison of peak flow and reach average width 4
Figure 4. Vegetation encroachment inside channel margins between 1992 and 2002 4
Figure 5. River Operations reaches 6
Figure 6. Digitized Rio Grande 2001 morphology near Santo Domingo, NM 8
Figure 7. Missing or cutoff historical channel near BDANWR 11
Figure 8. Comparison of valley length with and without LFCC levee. 13
Figure 9. Reach-averaged active channel width over time 15
Figure 10. Reach-averaged floodplain widths over time 16
Figure 11. Reach island area over time 17
Figure 12. Reach sinuosity over time 18
Figure 13. Channel width statistics over time for Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir 19
Figure 14. Channel width statistics over time for Middle Rio Grande between Cochiti Dam and Bernalillo. 21
Figure 15. Channel width statistics over time for Middle Rio Grande between Bernalillo and Isleta Diversion Dam 21
Figure 16. Channel width statistics over time for Middle Rio Grande between Isleta Diversion Dam and Rio Puerco. 22
Figure 17. Channel width statistics over time for Middle Rio Grande between Rio Puerco and Elephant Butte Reservoir. 22
Figure 18. Channel width statistics over time for Middle Rio Grande between Angostura Diversion Dam and Bernalillo. 23
Figure 19. Channel width statistics for Middle Rio Grande between the Rio Puerco and San Acacia Diversion Dam. 24
Figure 20. Sediment deposition upstream from San Acacia Diversion Dam in 1935. 25
Figure 21. Channel width statistics for Middle Rio Grande between Arroyo de las Canas and Hwy 380. 26
Figure 22. Aerial view of the 1918 and 1935 channels near the Highway 380 Bridge... 27
Figure 23. Cumulative channel cross section widths between Cochiti Dam and Elephant Butte Reservoir. 28

List of Tables

Table 1. River Operations reaches 6
Table 2. Reach-averaged active channel widths (feet) 14
Table 3. Percent change from previous data set in reach active channel widths 14
Table 4. Reach-averaged floodplain widths (feet) 15
Table 5. Percent change from previous data set in reach floodplain widths 15
Table 6. Reach island area (acres) 16
Table 7. Change from previous data set in reach island area (acres) 16
Table 8. Reach sinuosity 18
Table 9. Percent change from previous data set in reach sinuosity 18
Table 10. Channel width statistics for Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir. 19

1. Introduction and Background

In support of the Upper Rio Grande Water Operations, Environmental Impact Study, an assessment of the river channel and floodplain morphology is presented for the Middle Rio Grande valley (Figure 1) between the U.S. Army Corps of Engineers Cochiti Dam and the U.S. Bureau of Reclamation Elephant Butte Reservoir.

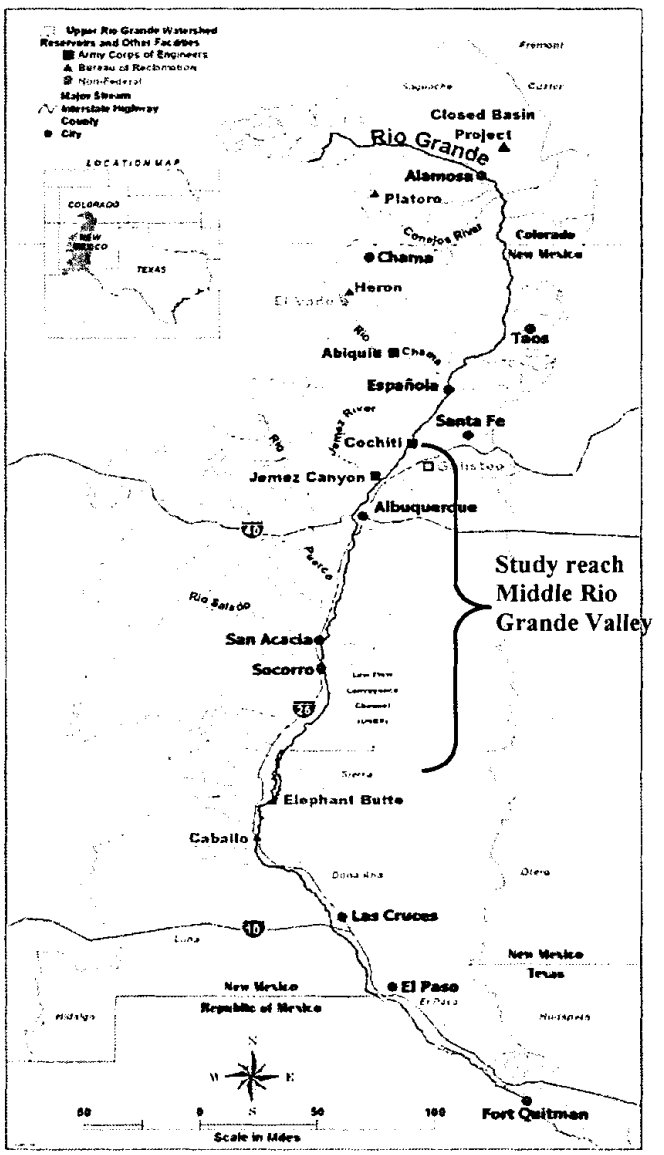


Figure 1. Upper Rio Grande basin and study reach

This study describes the temporal and spatial distribution of the river planform characteristics of channel width, floodplain width, and island area. The knowledge gained through this characterization will be useful in decisions concerning future

management of water operations because it documents natural and anthropogenic stresses to the system and the associated planform.

The Upper Rio Grande is an alluvial channel located primarily in the semi-arid state of New Mexico. The Upper Rio Grande Basin originates in the San Juan Mountains in southwestern Colorado. The Rio Grande passes through the San Luis valley and Alamosa, Colorado. Near the New Mexico border the Rio Conejos also joins the Rio Grande, which drains in a southeasterly direction. In northern New Mexico near the community of Espanola the Rio Chama joins the Rio Grande. Graf (1994) noted that the Rio Grande above Espanola yields more water and the Rio Chama produces more sediment. In the Middle Rio Grande valley, the Rio Grande encounters other tributaries that are ephemeral sediment producers such as the Rio Puerco and the Rio Salado. Below Elephant Butte Dam down to the terminus of the basin at Ft. Quitman, Texas, smaller flashy arroyos exist which mainly contribute sediment to the river channel.

2. River Morphological Influences

what ch-ge?

The flow regime of the Rio Grande has varied over time. There are two primary sources of change, climate and humans. Periods of extended drought or wet hydrology have in particular influenced the magnitude, duration, and frequency of channel forming flows and the river morphology. Based on the period of record for the Otowi Gage (representing inflow into Cochiti reservoir), hydrologically wet periods were experienced in the years 1927 – 1942 and 1972 – 1995 with dry periods occurring in 1924 – 1926 and 1943 – 1971. Another dry period began in 1996.

In the Upper Rio Grande Basin, anthropogenic influences to instream flows include: irrigation diversions and structures, water storage reservoirs, trans-mountain diversions, groundwater withdrawal, flood control dams and facilities, riverside water conveyance canals and drains, river channelization and grade control facilities. The major federal water delivery and flood control facilities include the following facilities with their corresponding year of establishment listed in downstream order: Alamosa Closed Basin groundwater wells and delivery canal (1980); Platoro Dam (1951); Heron Dam (1971); El Vado Dam (1935); Abiquiu Dam (1963); Cochiti Dam (1973); Galisteo Dam (1970); Jemez Canyon Dam (1953); the Low Flow Conveyance Channel (1959); Elephant Butte Dam (1916); and Caballo Dam (1938) as shown in Figure 2. These water delivery and flood control facilities have altered the magnitude, duration, and frequency of instream flows.

Large floods are modified through reduced peaks and delayed releases. Reduced peaks are illustrated by the comparison of the flood of 1941 with 22,000 ft^3/s at Otowi Bridge and 22,400 ft^3/s downstream of the Cochiti Dam site to the 1985 flood of 12,000 ft^3/s at Otowi Bridge and 8,290 ft^3/s downstream of Cochiti Dam. These floods occurred during hydrologically wet periods, but the second flood is reduced below Cochiti by nearly one third. Peak releases from Cochiti are less than 7,000 ft^3/s during the current dry period but average only 3500 ft^3/s.

The general effect of current river operations on the Middle Rio Grande morphology has been that peak flows have decreased in magnitude leading to a decrease in the river channel width (Figure 3). This decrease in width is also due in part to vegetation encroachment in the channel that may have been exacerbated by the reduction in peak flows and drought and the cessation of vegetation clearing in the Floodway (Figure 4). Note the open sandy channel in 1992 and the increase in vegetated islands and attached bars by 2002. The river channelization work during the 1950s and 1960s of straightening and jetty jack installation is another major factor in width reduction. The jetty jacks were installed to create a channel width of 550 – 600 feet, designed to more efficiently convey water and sediment.

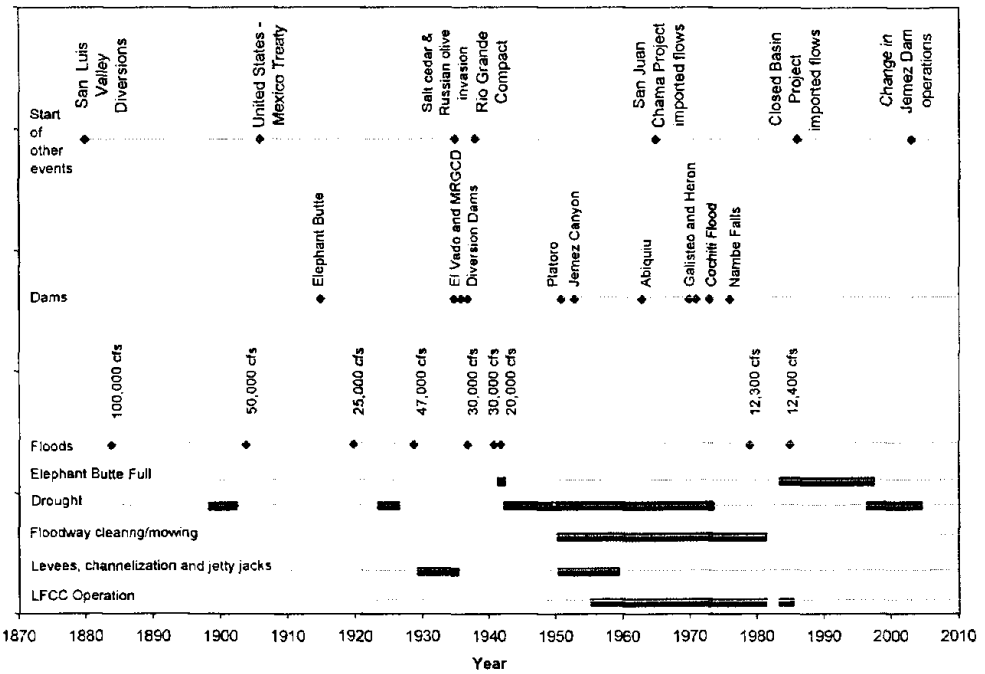


Figure 2. Timeline of significant events

The sediment supplied to the Middle Rio Grande has also changed significantly over time. The sources of change are similar to that of the flow regime, the establishment of major federal water delivery and flood control facilities and climate changes. Facilities such as Cochiti Dam, Galisteo Dam, and Jemez Canyon Dam have generally captured a significant portion of the sediment. The Kelner jetty fields also caused sediment deposition and storage allowing vegetation colonization which narrowed the river channel and increased the sediment transport capacity.

Climactic influences generally apply on larger, regional basis. Hereford (2002) postulates that the episodic increase of the frequency of large floods in the late 1800s resulted in historic arroyo cutting and a large increase in sediment supply to the river. Subsequent aggradation occurred during a period of infrequent large floods. These patterns are probably related to the El Nino-Southern Oscillation and its effects on atmospheric and oceanic circulation.

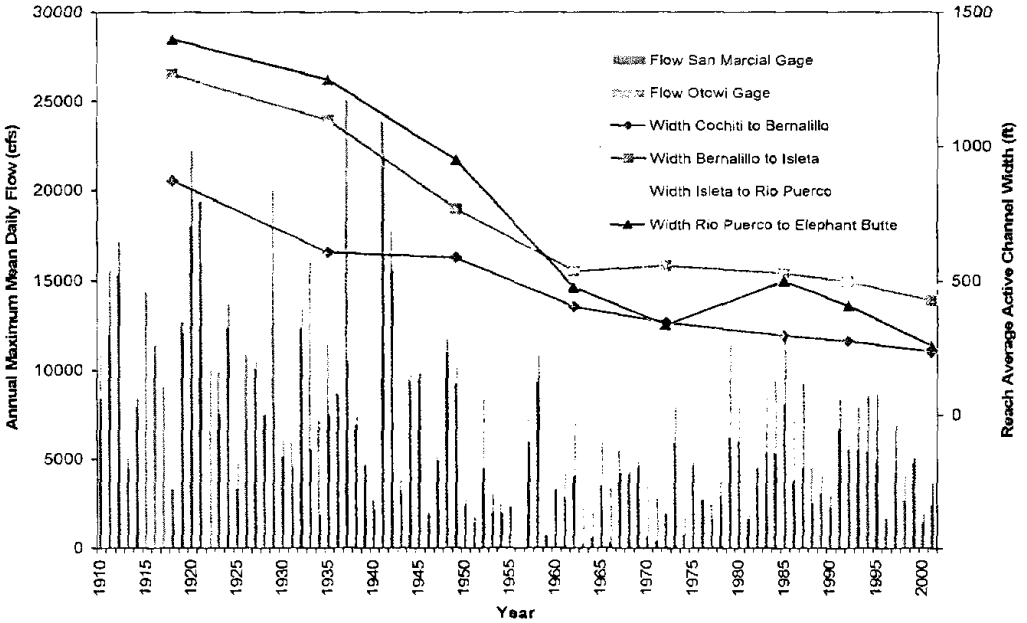


Figure 3. Comparison of peak flow and reach average width

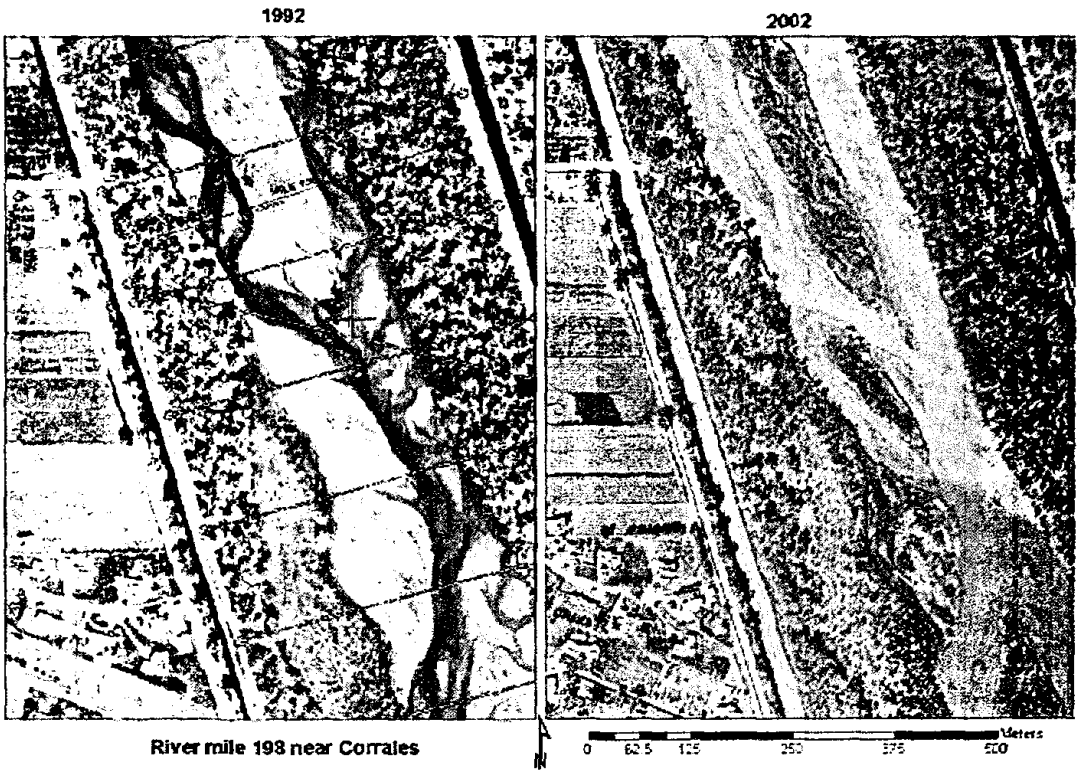


Figure 4. Vegetation encroachment inside channel margins between 1992 and 2002

In the Upper Rio Grande basin, physical processes that influence the river morphology are dependent on the basin hydrology, river hydraulics, sediment supply and transport, riverbed topography, bed sediment size, and vegetation. When one or more of these change, the river may respond with a change in morphology. The direction of a channel's response is easier to ascertain than the magnitude or rate. The simplest description of the relationship between water and sediment is Lane's equation (Lane 1955)

$$Q_s\, d \propto Q_w\, S$$

Where

Q_s	=	sediment load (of sizes represented in the riverbed),
d	=	sediment particle diameter of the riverbed,
Q_w	=	water discharge, and
S	=	river channel slope.

In other words, $Q_s d$ is proportional to $Q_w S$. For example, the discharge released from a reservoir is usually clear water (low in sediment) and Lane's relationship implies the downstream channel slope will flatten to reduce the stream's energy and the sediment transport capacity. The size of sediment particles may control the extent of degradation. If the channel becomes armored such that the discharge cannot transport the larger particles; the sediment transport capacity may still be unmet from bed degradation alone. The sediment transport capacity may also be at least partially met by bank erosion and lateral migration, a process not described by the Lane relationship.

This assessment does not directly describe the individual effects of various anthropogenic, geologic, hydrologic, and climatic influences on the river's morphology. Given the broad scope of these influences to the river's morphology, such an endeavor would be difficult to accomplish within the scope of this characterization and assessment. Therefore, a qualitative discussion of the cause and effect relationships between natural/anthropogenic influences and river's planform morphology and pattern are presented.

3. River Operations Reaches

The study reach has been sub-divided, as shown in Table 1 and Figure 5, into four reach designations representing river channel areas that share similar processes. Two dams, a change in planform/bed material, a tributary confluence, and a reservoir boundary serve as physical landmarks for the reach boundaries. The planform/bed material change is at Bernalillo, which was the southernmost point where the river bed was a single thread, coarser bed channel when the study began. This point has migrated downstream and in 2004 is near Rio Rancho/Corrales. ? when did study begin

The Middle Rio Grande Aggradation/Degradation (agg/deg) rangelines (Abram, 1962) are also used to identify the reaches. The rangelines are historical cross sections established in the study reach to monitor the morphologic condition of the river channel. These rangelines, established in 1962, include the channel and floodplain and are spaced at approximately 500 foot increments along the river. The agg/deg rangeline locations are generally perpendicular to the river. The final column in Table 1 contains the corresponding river miles (from the 1972 alignment) where Caballo Dam is river mile zero and miles increase in the upstream direction.

Table 1. River Operations reaches

Reach	Name	Agg/Deg Lines	River Miles
Cochiti Dam to US 550 at Bernalillo	COBL	19-298	233-204
US 550 at Bernalillo to Isleta Diversion Dam	BLIS	298-655	204-169
Isleta Diversion Dam to Rio Puerco Confluence	ISRP	655-1099	169-127
Mouth of Rio Puerco to Elephant Butte Reservoir	RPEB	1099-1790	127-61

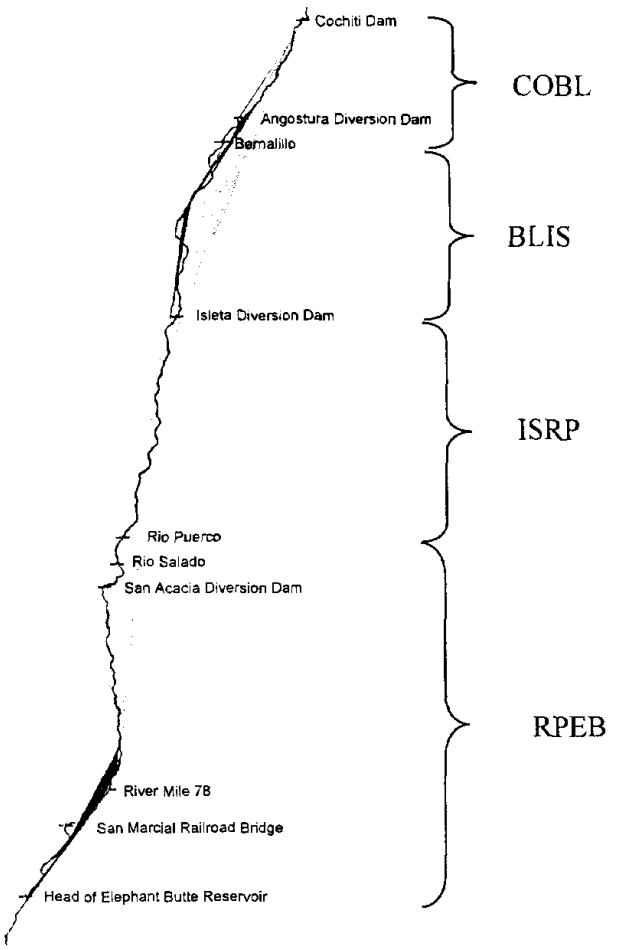


Figure 5. River Operations reaches

The most upstream reach is between Cochiti Dam and the US 550 (NM 44) Bridge in Bernalillo (COBL). Moving downstream, the next reach is from Bernalillo to Isleta Diversion Dam (BLIS). Next is the reach from Isleta Diversion Dam to the mouth of the Rio Puerco (ISRP). The last reach runs from the mouth of the Rio Puerco to Elephant Butte Reservoir (RPEB). Differences in river processes described in Makar and Strand (2002), Massong et. al. (2001), and Richard et. al. (2001) indicate that additional subreach divisions at San Acacia Diversion dam and near rivermile 78 may also be useful.

Agg/deg rangeline 1790 (River mile 61) was selected as the endpoint for this study for several reasons. First, the 1935 data ends there. This rangeline is near the conveyance channel outfall at station 1800 and is also near the full reservoir pool boundary. During the dry period of the 1940s through the 1970s, the head of the reservoir receded to the Narrows of Elephant Butte reservoir (downstream of agg/deg 1962). The head of the reservoir is currently (2003) below the Narrows. During periods of lower pool elevation, the floodway between agg/deg 1790 and the reservoir pool becomes more riverine in character, to a large extent due to mechanical efforts to maintain a viable channel to the reservoir.

4. Methods

Reach average values for the channel width, floodplain width, island area, and sinuosity were calculated from digitized information in the Rio Grande GIS database (Oliver 2004). These variables are used to quantify changes in the planform river morphology both temporally and spatially. Channel widths for individual agg/deg lines are used to assess changes in variability.

4.1 GIS Database

Planform data in the form of maps and aerial photographs are available in the GIS database for eight data sets during the time period 1908 to 2001 (see Figure 2). Figure 6 is an example of the digitized morphology. The materials used to create the GIS database used in this study were Middle Rio Grande Project mapsheets, black and white aerial photography, tabular data and graphs, and hand-drafted linens obtained from the Albuquerque Area Office of the United States Bureau of Reclamation. The scale of the image-based source material varies and is 1:4800 for 1949, 1962, 1972, 1984/1985, 1992 and 2001. The 1949 images are photo-mosaics, the 1962, 1972, and 2001 images are ratio-rectified photo-mosaics and the 1984/1985 and 1992 images are ortho-photos. The Rio Grande upstream of Belen was photographed in 1984 and downstream in 1985 by two different companies. The scale of the enlarged photo-mosaics for 1935 is about 1:8000. Mapsheet scale estimations were derived from the ratio of the distance between two points which could be located on both the 1935 photo-mosaic and the 1992 ortho-photo mapsheet. The scale of the 1918 maps drawn on linen is 1:12000. All aerial photography is black and white. The orthophotos and photo-mosaics are printed on mylar except 1949, which are on acetate film, and the 1935/1936 mosaics which are on photographic paper. The 1918 data ends downstream of San Marcial, but a 1908 map, at a smaller scale, shows a river channel through Truth or Consequences. Because this is a

short, very narrow section of valley and channel, the two data sets were combined for this analysis. Metadata (Oliver 2004) that accompanies this database documents the categories of data and the limitations and sources of the data in detail.

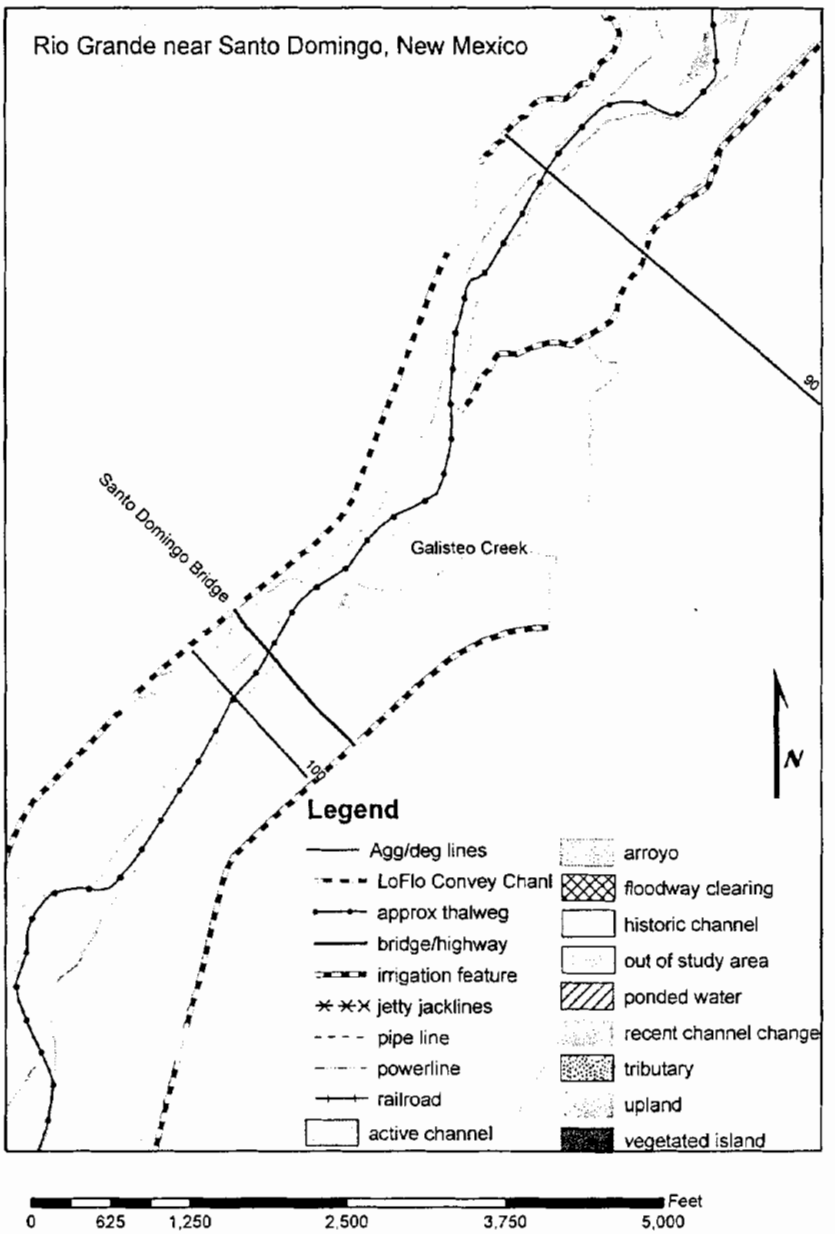


Figure 6. Digitized Rio Grande 2001 morphology near Santo Domingo, NM

4.2 Geomorphic categories

Several categories in the GIS database are not immediately intuitive nor simple. For ease of reference, brief definitions of the categories are as follows:

- Active channel – area between the mature riparian vegetation bank line
- Arroyo – areas of intermittent tributaries that contribute sediment
- Floodway clearing - areas bordering the active channel that were mechanically cleared
- Historic channel - area once occupied by the active river channel
- Out of study area – areas outside of confining levees and terraces or mesa
- Ponded water – areas of standing water
- Recent change - areas cleared or abandoned by the river between years of photography
- Tributary – large, more frequently flowing tributaries
- Upland – areas of non riparian vegetation or agriculture
- Vegetated island – areas surrounded by channel with mature vegetation

Detailed discussions on specific categories pertinent to this study can be found in the following sections.

4.3 Active Channel Width

The digitized active channel was classified as the area between the mature vegetation riparian boundary lines on either river bank and includes sandy areas cleared of vegetation by the river. The channel areas labeled *sand* on the 1918 linens were assumed to be similar to the cleared sandy areas observed in the aerial photos and so digitized. Where possible, the areas bulldozed for floodway clearing activities were assigned to a separate category. It should be noted that where the 1918 and 1908 channels overlap, they are in the same location but **not** the same width and the 1918 width is used where available.

For this study, the active channel width is assumed equivalent to the riparian boundary and does not include vegetated islands. A reach-averaged value for active channel width was calculated two different ways. For the first method, the width of the active channel was summed along the agg/deg rangelines then divided by the number of the rangelines within a reach. The agg/deg lines are not always perpendicular to the channel or the flow path, resulting in a potential error in the channel widths for method 1. In the second method the area of the active channel between the reach defining agg/deg rangelines was calculated from the GIS database. This area was divided by the length of the centerline of the channel. The centerline was used because a low flow thalweg is generally much more sinuous than the centerline of the channel formed at high flows. Method 2 was used to calculate the reach averaged width values reported here. This method does not provide any information on the variability of widths within a reach, so method 1 is used in a separate analysis of channel width variability statistics.

4.4 Floodplain Width

The floodplain width reported is not based on hydraulic modeling of a specific discharge, but is a visual representation of the potential floodplain that was digitized from the 1935 photos. The floodplain area was edited from the GIS coverage to be the area between confining levees, when present, or up to the historical channel/upland boundary in the absence of levees. Adjustments were made to the coverage for changes in levees and bank erosion along the Rio Grande channel for the years 1949, 1962, and 1992. The 1918 geomorphology coverage includes only the active channel since the hand-drawn maps did not have enough information to delineate the floodplain. The 1962 coverage was compared to the 1992 coverage and little change was evident. It was assumed the 1972 and 1984/5 floodplain boundaries were not significantly different and therefore were reported. Little change was noted between 1992 and 2001 during digitizing, so 2001 floodplain boundaries were also not edited or reported. In some locations and years, the floodplain area was cut off at the edge of the map. This missing area varied among the different sets of data, and could change the value calculated for reach-averaged floodplain width. Figure 7 illustrates the cutoff near the Bosque del Apache National Wildlife Refuge (BDANWR).

The method used to define floodplain area was initially to combine the polygon categories of active channel, recent change, vegetated islands, floodway clearing, and historical channel and exclude upland areas. Areas under cultivation in the floodplain were digitized as upland under the assumption that these areas would be defended from flooding. For this analysis, agricultural clearings in the 1935 and 1949 riparian/historical channel/floodplain were edited to be included in the floodplain polygons unless the clearings were protected by levees. Where upland uses destroyed clear evidence of river activity, the area was categorized as upland in the database. Agricultural clearing was more abundant in the 1935 data but much of the clearing was abandoned after 1935. Riparian vegetation had reclaimed a good deal of the abandoned area by 1949 and so was included as part of the floodplain.

Confining levees were used as limits to the extent of the floodplain areas. Where levees didn't connect across arroyos or drains, a direct line closed the area with the closest confining feature because there was insufficient data to determine the extent of flooding up the arroyo. Generally, the area of these fans was determined to not be significant enough to warrant the time to edit them in the GIS floodplain coverages. An exception was the Rio Salado alluvial fan that was quite large in 1935 but diminished in size by 1949. The floodplain definition in the fan area was not altered from the direct line procedure described above because of the lack of elevation data.

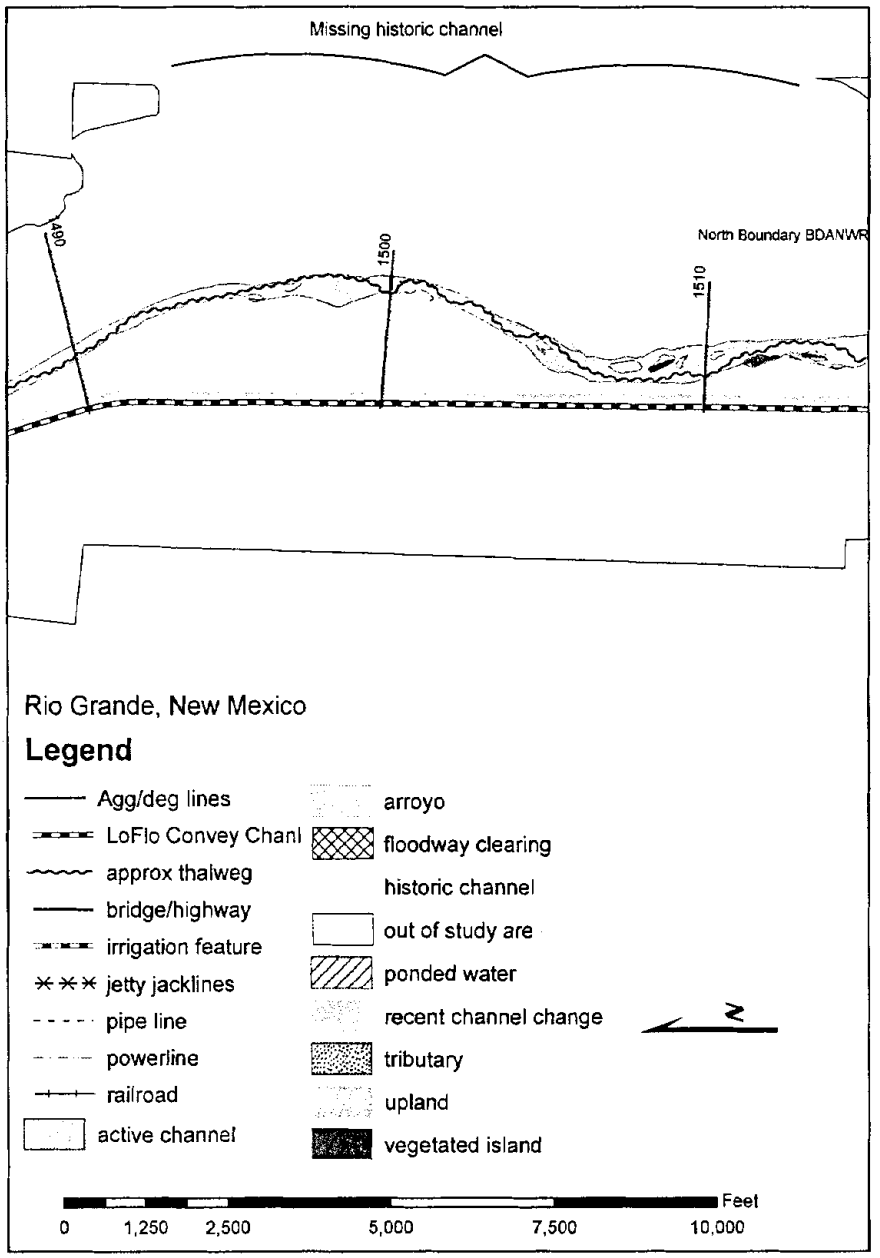


Figure 7. Missing or cutoff historical channel near BDANWR

The 1935 photography did not always cover the entire floodplain, e.g. the east side of the Rio Grande in the area immediately above the Rio Salado. Where data was missing in 1935, the 1949 floodplain was used to complete the 1935 data for the purpose of these

measurements. The same methodology was used in reverse for the area above San Acacia Diversion Dam where data was available for 1935 but not for 1949.

Floodplain width was calculated three ways. In the first two methods, the reach floodplain area, as defined above, was divided by length. The first method used channel centerline length and the second used valley length. Changes in valley length during different time periods are discussed section 4.5. For the third method, the floodplain width measurements were collected using an edited version of every 10th agg/deg line. The selected rangelines were extended and/or rotated, where required, such that they crossed the floodplain without intersecting adjacent agg/deg lines. Again, these rangelines were not always perpendicular to the channel or valley. The measured floodplain widths were then averaged within the defined reaches. The floodplain area divided by valley length was then used for width calculation in this study (method 2) for consistent trend comparison with the active channel widths. Widths are reported to the nearest 50 feet due to the data issues discussed above.

4.5 Island Area

The current Rio Grande GIS classification of a vegetated island describes areas of vegetation exceeding several seasons of growth separated from the historical channel by active channel, and in some instances, surrounded by a combination of active channel and recent change in the active channel. This definition evolved when the Cochiti Dam to San Acacia Diversion Dam reaches were digitized as discussed below.

Digitizing of islands began in the San Acacia Diversion Dam to Elephant Butte area. Originally, a vegetated island was defined as vegetation surrounded by active channel. In some cases, an abandoned channel might cause an isolated area of vegetation to be separated from the historical channel by an area of recent change. The sparsely vegetated or rocky debris was not active channel, so in this scenario the isolated mature vegetation continued to be classified as historical channel rather than as an island.

When digitizing the Cochiti Dam to San Acacia Diversion Dam area, there was not always a clear distinction between an abandoned channel versus a new channel developing. Identification of an island developing as a result of a new channel was not always clear. The classification definitions were broadened to reduce the number of categories. This change proved useful when identifying where the jetty jack lines changed the flow path or where pilot channels were cut through the historical channel because of the uncertainty in channel identification as discussed above.

As a result of the broadened island classification, island area data for all reaches included both "isolated historical channel" and "islands attached to the historical channel by recent change." Both of these areas were further identified as "attached." The reach-averaged island areas, with and without attached islands, were compared. There was little difference between the results except downstream of San Acacia from 1962 and later because of the change in island identification. To ensure a consistent interpretation for the entire study, the island areas with "attached" data are reported.

4.6 Sinuosity

Sinuosity is defined as the length of the channel divided by the valley length. In the GIS database, two channel lengths were available - the length of the channel centerline and the length of the thalweg. The thalweg length is more appropriate for analysis of low flows and results in a higher calculated sinuosity. The length of the channel centerline is more pertinent to bankfull discharge. Other data in this study are dependent on bankfull discharge so sinuosity based on channel centerline is reported. Valley length is the shortest distance the river could travel measured down the valley. This length is modified in some areas due to levees or other structures that limit river movement. For example, downstream of San Acacia Diversion Dam the Low Flow Conveyance Channel (LFCC) levee limits the area available for channel movement and thereby extends the valley length, as shown in Figure 8.

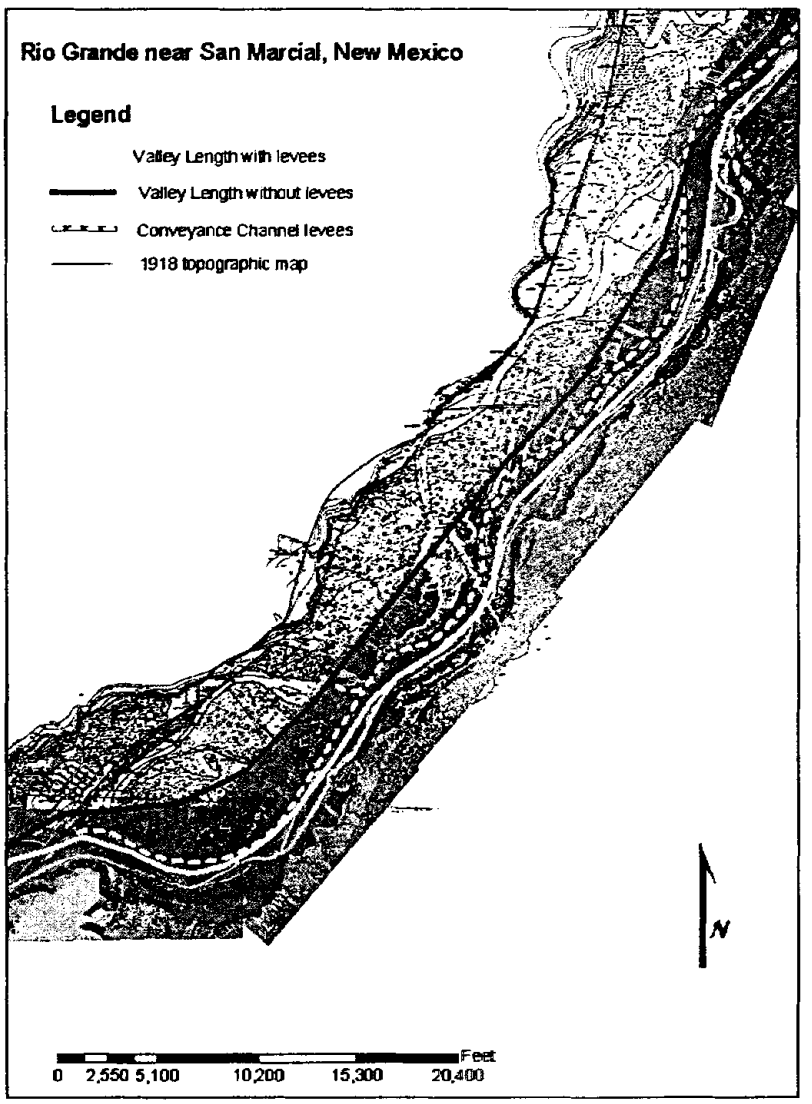


Figure 8. Comparison of valley length with and without LFCC levee.

5. Results and Discussion

Mean values of width, floodplain width, island area and sinuosity changes are presented to facilitate comparison of these variables by reach over time.

5.1 Active Channel Width

Table 2 and Figure 9 present the reach-averaged active channel widths by year. Table 3 presents the total and yearly percentage change between datasets.

Two trends are apparent. Width generally decreases over time through 1962. Much less change is noted from 1962 to 1992, due in part to channel maintenance. The change in hydrology from a dry period to a wet period with greater discharges is likely the source of the increases noted from 1972 to 1984/5 in the ISRP and RPEB subreaches. The narrowing seen in 2001 is in most cases the result of island and bar formation during a period of low flow. The persistence of these channel features will be a function of the size of future flows and vegetation growth.

Table 2. Reach-averaged active channel widths (feet)

Year	COBL	BLIS	ISRP	RPEB
1918	870	1270	1240	1400
1935	610	1100	1080	1250
1949	590	770	720	950
1962	410	540	470	480
1972	350	560	470	340
1984/5	300	530	500	500
1992	280	500	500	410
2001	240	430	480	260

Table 3. Percent change from previous data set in reach active channel widths

		COBL		BLIS		ISRP		RPEB	
Year	Years between data sets	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)
1935	17	-30	-2	-14	-1	-13	-1	-11	-1
1949	14	-4	0	-30	-2	-34	-2	-24	-2
1962	13	-30	-2	-30	-2	-35	-3	-50	-4
1972	10	-14	-1	4	0	0	0	-30	-3
1984/5	12/13	-14	-1	-5	0	8	1	48	4
1992	7/8	-7	-1	-5	-1	0	0	-18	-3
2001	9	-13	-1	-14	-2	-5	-1	-35	-4

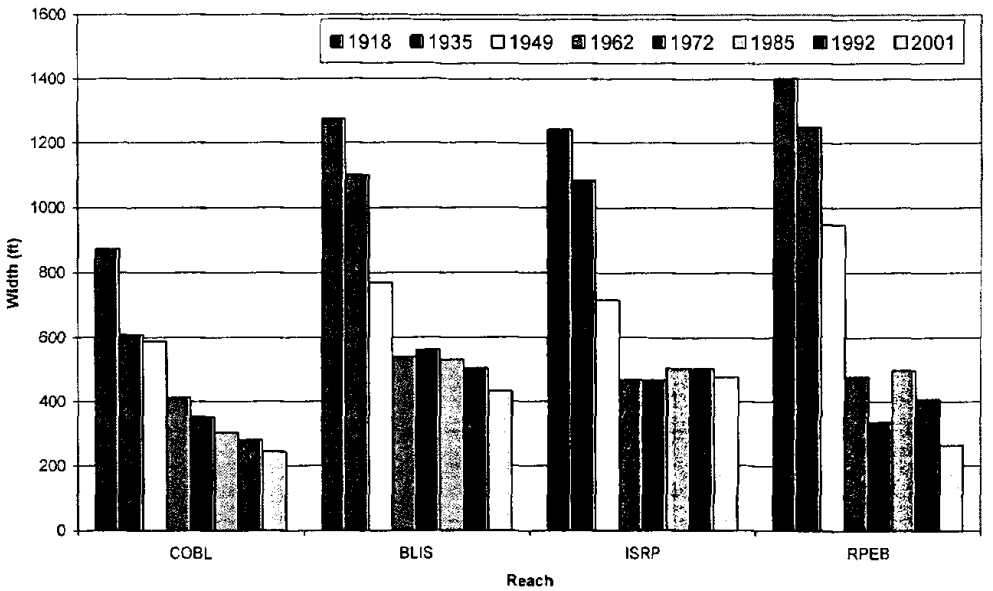


Figure 9. Reach-averaged active channel width over time

5.2 Floodplain width

Floodplain widths follow a similar pattern of significant decrease between 1949 and 1962 as shown in Tables 4 and 5 and Figure 10. Again, no interpretation of floodplain data was possible from the 1918 linens. The large decrease in RPEB from 1949 to 1962 is due to the floodplain cutoff by the LFCC construction. The general increase from 1935 to 1949 is attributed to cases where land cleared in the 1935 photos could not be positively identified as floodplain and then showed up as riparian vegetation in 1949 (see floodplain width discussion in section 4). Little difference in floodplain widths was seen between 1962 and 1992 except for the reduction due to the Drain Unit 7 extension near the Rio Puerco, so data for 1972 and 1985 were not calculated. It has also been assumed that the lack of change extends into 2001.

Table 4. Reach-averaged floodplain widths (feet)

Year	COBL	BLIS	ISRP	RPEB
1935	2000	1900	2250	4300
1949	2400	1950	2400	4300
1962	2000	1800	2050	2500
1992	2000	1800	2050	2450

Table 5. Percent change from previous data set in reach floodplain widths

		COBL		BLIS		ISRP		RPEB	
Year	Years between data sets	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)
1949	14	20	1	3	0	7	0	0	0
1962	13	-17	-1	-8	-1	-15	-1	-42	-3
1992	20	0	0	0	0	0	0	-2	0

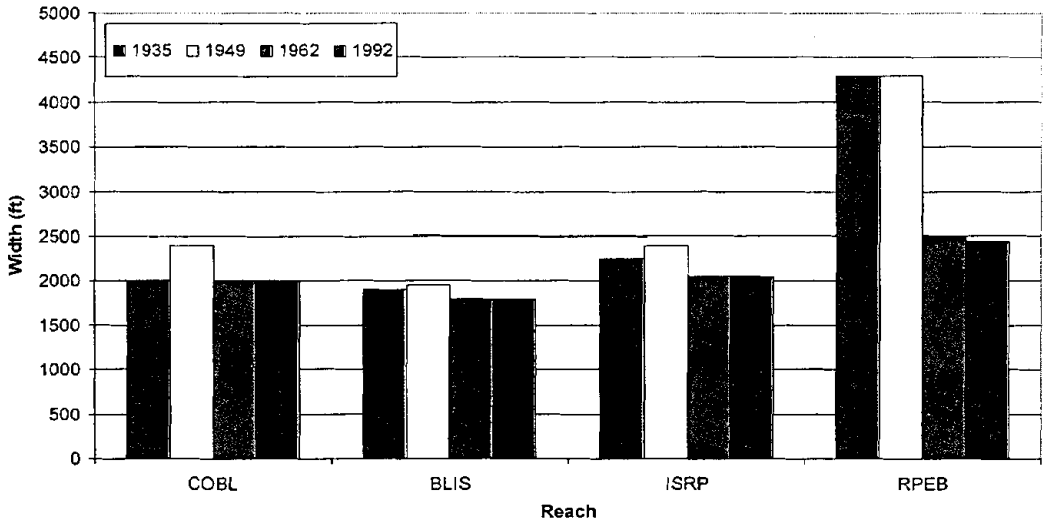


Figure 10. Reach-averaged floodplain widths over time

5.3 Island area

Island area trends over time were much less consistent than either active channel or floodplain widths. Tables 6 and 7 and Figure 11 show this complexity.

Table 6. Reach island area (acres)

Year	COBL	BLIS	ISRP	RPEB
1918	2060	490	650	430
1935	440	360	870	540
1949	620	250	340	130
1962	440	170	90	430
1972	220	50	30	350
1984/5	150	40	0	210
1992	210	110	10	110
2001*	230	320	90	270

* Some of this increase may be attached bars with water next to the original bankline

Table 7. Change from previous data set in reach island area (acres)

	Years	COBL		BLIS		ISRP		RPEB	
Year	between data sets	Total change	Change per year	Total change	Change per year	Total change	Change per year	Total change	Change per year
1935	17	-1620	-95	-130	-8	220	13	110	6
1949	14	180	13	-110	-8	-530	-37	-410	-30
1962	13	-180	-14	-80	-7	-250	-19	300	23
1972	10	-220	-22	-120	-12	-60	-7	-80	-8
1984/5	12/13	-70	-6	-10	-1	-30	-2	-140	-11
1992	7/8	60	8	70	8	10	<1	-100	-14
2001	9	20	2	210	23	80	10	160	17

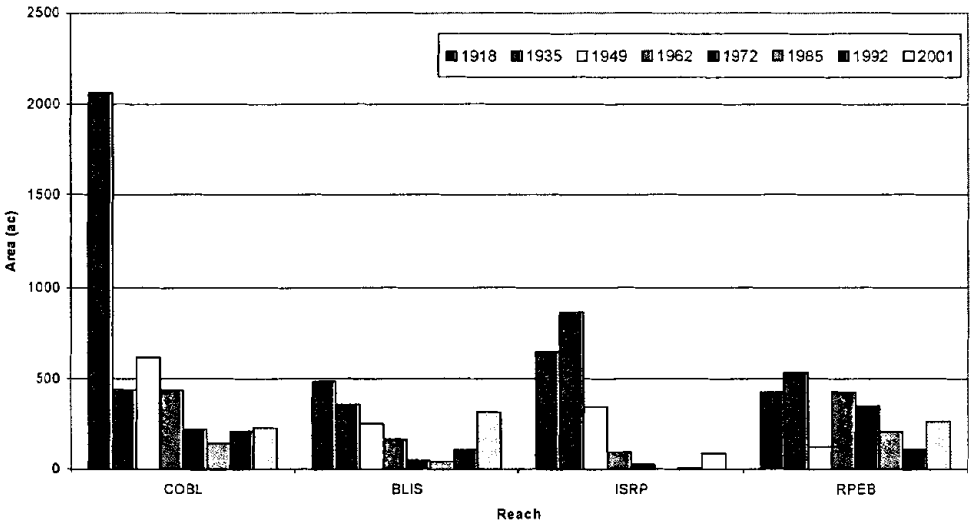


Figure 11. Reach island area over time

In the COBL reach, the 1918 linens showed a multi-channel, anastomosing river with large islands between the channels. Later photos showed less than one-third the area of islands in the same reach. Difficulties in interpreting the maps were the largest in the RPEB reach, particularly in 1918 and 1949. The 1918 data for the most downstream portion of this reach was from a 1908 map as noted previously. The 1908 scale is much smaller and the data for the islands on that map were probably not representative. The 1949 photos showed evidence of recent high flows, with discontinuous water and "fingering" of the channel in the RPEB reach. Again, the data for the islands may not be representative. The reduced discharges and vegetation growth during the dry period after 1992 is the likely cause of much of the island increase shown in 2001 for all reaches. These new island areas may be eroded when higher flows return.

5.4 Sinuosity

The Middle Rio Grande is a straight river with a sinuosity of less than 1.2 in all reaches as shown in Table 8. Changes between years are very small, see Tables 8 and 9 and Figure 12. The COBL and RPEB reaches were less sinuous than the BLIS and ISRP reaches. The sinuosity drops between 1949 and 1962 due in large part to channelization activities of straightening and jack and levee construction. These activities generally continue to limit lateral migration. The recent minor increase in sinuosity is primarily due to channel narrowing and island formation.

Table 8. Reach sinuosity

Year	COBL	BLIS	ISRP	RPEB
1918	1.07	1.13	1.12	1.10
1935	1.06	1.12	1.11	1.09
1949	1.08	1.14	1.13	1.10
1962	1.08	1.12	1.10	1.05
1972	1.05	1.11	1.10	1.05
1984/5	1.07	1.12	1.09	1.03
1992	1.09	1.12	1.10	1.03
2001	1.10	1.14	1.10	1.05

Table 9. Percent change from previous data set in reach sinuosity

		COBL		BLIS		ISRP		RPEB	
Year	Years between data sets	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)	Total change (%)	Change per year (%)
1935	17	-1	<-0.1	-1	<-0.1	-2	-0.1	-1	<-0.1
1949	14	2	0.1	2	0.1	2	0.2	1	<0.1
1962	13	<-1	<-0.1	-1	<-0.1	-2	-0.2	-4	-0.3
1972	10	-3	-0.3	-1	<-0.1	<-1	<-0.1	<1	<0.1
1984/5	12/13	3	0.2	<1	<0.1	<-1	<-0.1	-2	-0.2
1992	7/8	1	0.2	<1	<0.1	<1	<0.1	<1	<0.1
2001	9	1	0.1	2	0.2	<1	<0.1	1	0.2

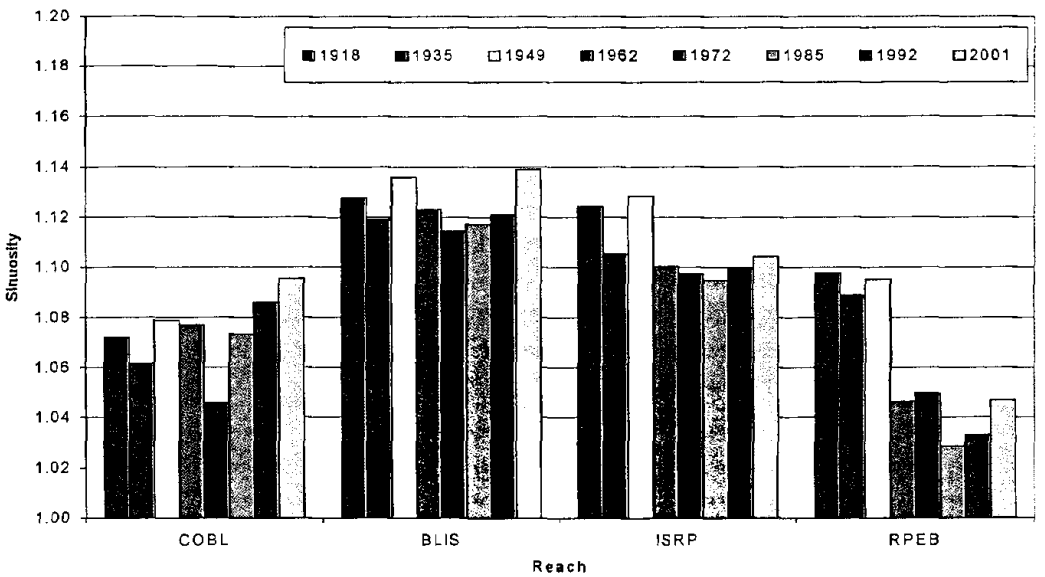


Figure 12. Reach sinuosity over time

5.5 Width Analysis

For each year of data, widths by individual cross section (method 2 in section 4.2) were tabulated and statistically analyzed as shown in Table 10 and Figure 13. Analysis includes mean, median, inter-quartile range, maximum, minimum, and standard deviation. The inter-quartile range measures the spread of the central 50 percent of the data (Hensel and Hirsch 1992). General trends for the entire study reach and detailed descriptions for specific areas follow.

Table 10. Channel width statistics for Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir.

Statistic	1918	1935	1949	1962	1972	1985	1992	2001
Mean	1320	1130	780	470	400	480	440	360
Standard Deviation	750	670	540	330	280	300	240	170
Minimum	150	140	20	20	30	40	60	50
Maximum	5350	5150	3320	2170	1990	1940	1570	940

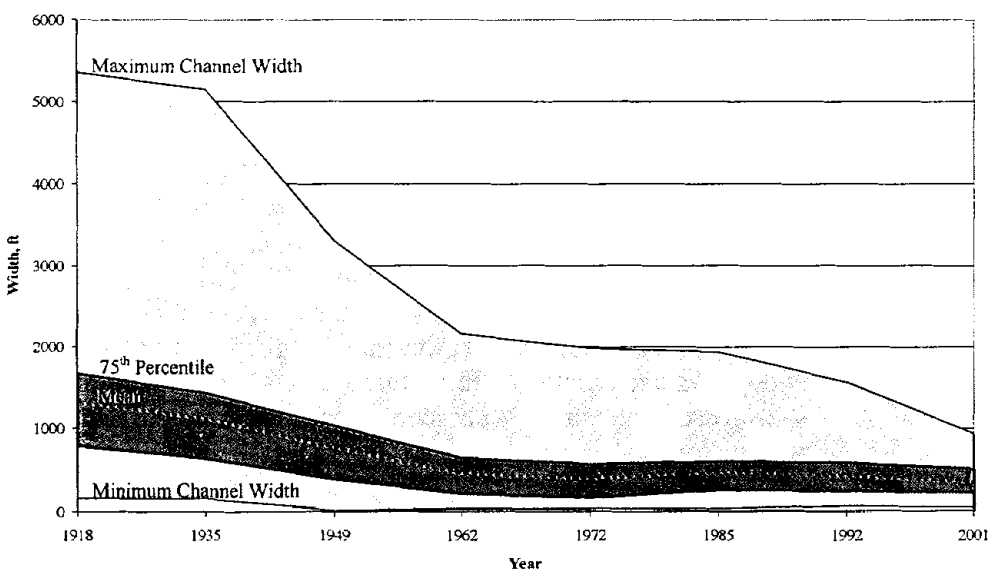


Figure 13. Channel width statistics over time for Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir.

In general, as discussed previously, widths were widest in 1918 and decrease over time. In 1918 and 1935, the river was very wide. Mean and maximum channel widths (table 10) are greater than 1,000 feet and 5,000 feet respectively. Decreases in width between

1918 and 1935 can be partially attributed to construction of riverside irrigation facilities such as drains and canals that are protected by levees. Widths in 1949 are still very wide compared to present values, but are less than earlier values. Mean and maximum width values decreased to 800 feet and 3,300 feet, respectively. Despite extensive flooding in 1941 (Scurlock 1998), widths had decreased by 1949. Beginning in 1943, drought conditions prevailed and the river channel narrowed by vegetation encroachment on bars and islands that were no longer flooded. By 1962, the mean channel width decreased to less than 500 feet and the maximum channel width decreased to less than 2,200 feet. Drought conditions were still prevalent in 1962, but narrowing was also due to mechanical channelization. Beginning in the 1950s, large sections of the river were narrowed with jetty jacks to more efficiently transport water and sediment downstream. The jacks also trapped sediment and protected the banks. The LFCC between San Acacia Diversion Dam and Elephant Butte Reservoir diverted up to 2000 ft^3/s from the floodway from the late 1950s through the early 1980s. With minor exceptions, the LFCC has not been operated since then, increasing the flows in the floodway. Widths continued to narrow through 1972 as mean channel width decreased to 400 feet. Drought and channelization were largely responsible for the narrowing. Prior to 1985, large sections of the river (floodway) were cleared of vegetation to maintain flood capacity. By 1985, the active channel width widened to near the edge of the cleared floodway. During the period 1979 to 1985, there were high flows in the river. Mean channel width decreased in 1992 and again in 2001. General floodway clearing had stopped before 1992 and vegetation started growing in areas that were not subjected to erosive floodwaters.

Trends for the entire study reach largely hold true for the sub-reaches, see Figures 14-17. The rate of decrease was greatest between 1918 and 1962. After 1962, the magnitude of change has been small compared to changes from 1918 and 1962. Similar to the mean width, the interquartile range has also decreased with the largest changes occurring before 1962 and with smaller changes after 1962. Changes in minimum channel width are small, but the greatest rate of change was before 1962. The largest amount of change has been in the maximum channel width. Maximum width values have decreased over 4,000 feet. The greatest rate of change in maximum width was between 1935 and 1949. Between 1962 and 1985, maximum width values decreased slightly. After 1985, maximum width values began decreasing at a faster rate and reached a minimum in 2001. Each period of rapid decrease in maximum width corresponds to periods of bar attachment and island development.

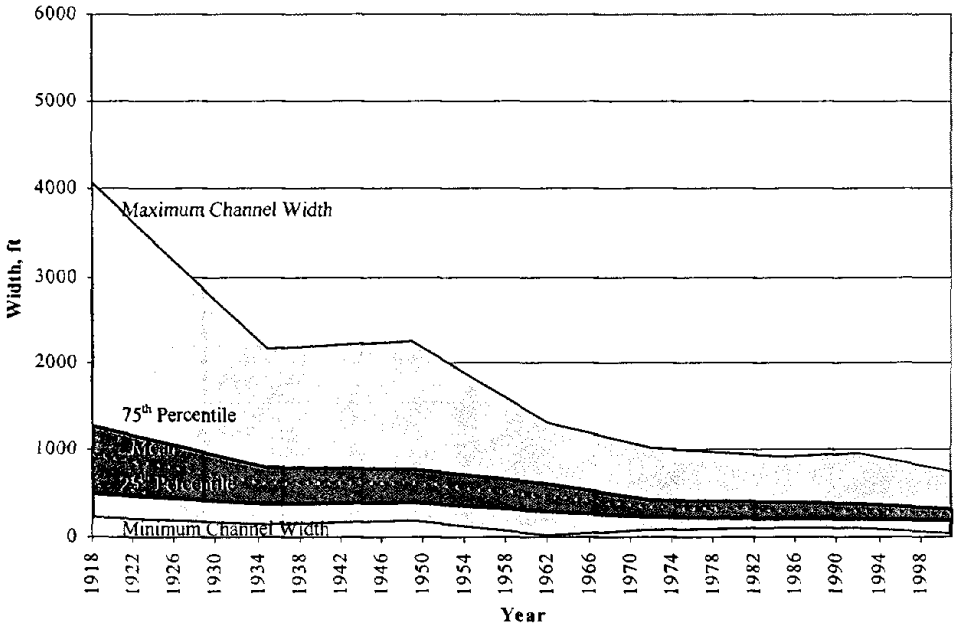


Figure 14. Channel width statistics over time for Middle Rio Grande between Cochiti Dam and Bernalillo.

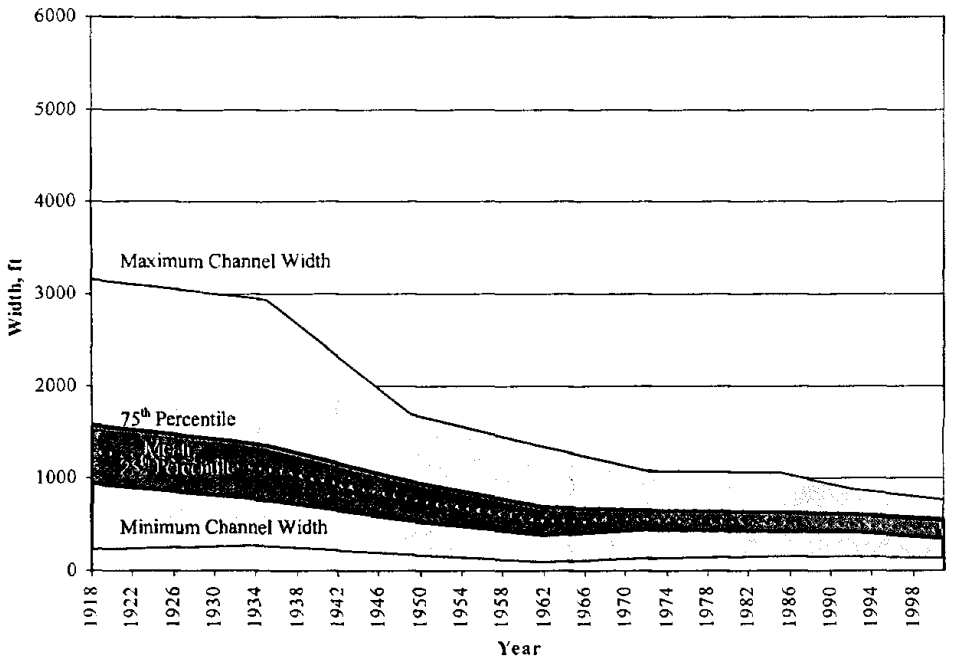


Figure 15. Channel width statistics over time for Middle Rio Grande between Bernalillo and Isleta Diversion Dam.

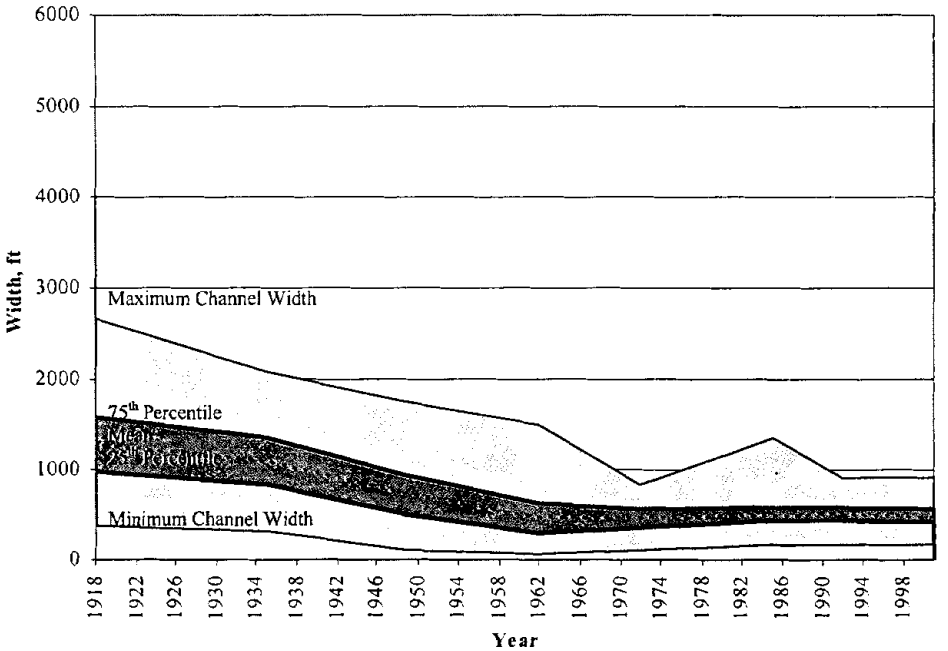


Figure 16. Channel width statistics over time for Middle Rio Grande between Isleta Diversion Dam and Rio Puerco.

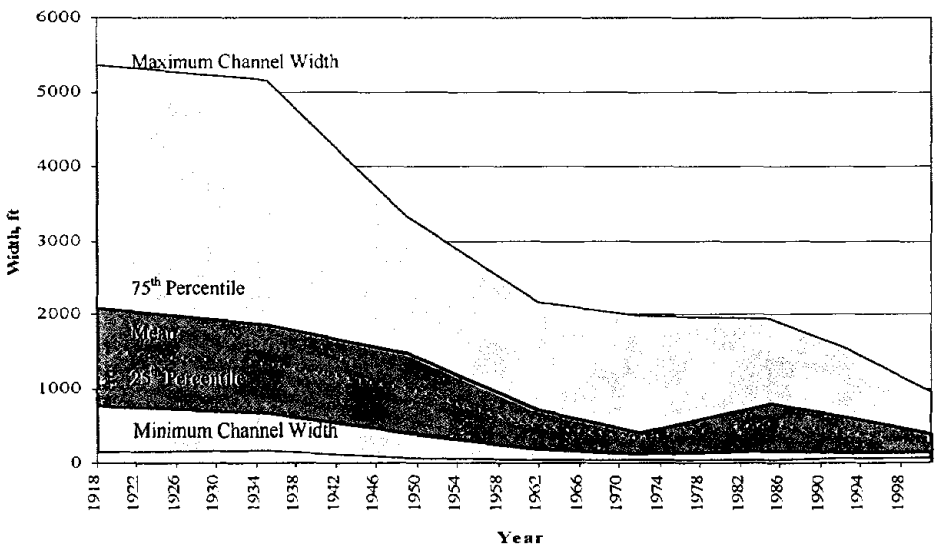


Figure 17. Channel width statistics over time for Middle Rio Grande between Rio Puerco and Elephant Butte Reservoir.

Additional graphs with shorter subreaches can be found in Appendix A. There are a few short subreaches that are exceptions to the general trends. In the area between Angostura Diversion Dam and Bernalillo (river mile 210 – 204), the width increased between 1935 and 1949 (see Figure 18). The increase in width may be related to the 1941 flood.

Historical accounts (Scurlock 1998) indicate that the Jemez River experienced severe flooding, which may have deposited large amounts of sediment in the channel downstream from the mouth of the Jemez River. This influx of sediment may have caused the Rio Grande to temporarily aggrade and widen. The widening would also have a limited range due to geologic constrictions near river mile 210 at the upstream end and near river mile 206 at downstream end of the area.

Another area that does not fit the general trend is between the mouth of the Rio Puerco and San Acacia Diversion Dam. In this reach, the maximum channel width decreased each year data was collected, however the mean width increased between 1918 and 1935 (see Figure 19). Examination of aerial photographs from 1935 suggests that the increase in mean channel width between 1918 and 1935 and the decrease in 1949 may be due to a combination of events including flooding on the Rio Puerco and construction of San Acacia Diversion Dam (river mile 126.5 – 116). In the 1935 photos, there is evidence of terraces near the mouth of the Rio Puerco that still exist. This suggests that aggradation near the mouth of Rio Puerco, and therefore sediment inputs to the Rio Grande, had occurred prior to 1935. The width increase between 1918 and 1935 may be in response to the high sediment loads coming from the Rio Puerco, especially during the 1929 flood where flows were over 30,000 ft^3/s (Scurlock 1998). In addition, photographs show the area immediately upstream from San Acacia Diversion Dam as being very similar to a delta entering a reservoir. The diversion dam was constructed in 1934 at a natural geologic constriction and sediment was trapped upstream from the dam creating a wide flat surface similar to that of a delta (see Figure 20). The decrease in width between 1935 and 1949 is likely the result of channel incision though deposited material. As sediment supplies decreased, it is likely that the channel began to incise and narrow. As the channel narrowed, velocity would have increased leading to further incision and narrowing very similar to a feed back loop. The drought conditions beginning in the 1940s tempered the trend with less water to transport sediment.

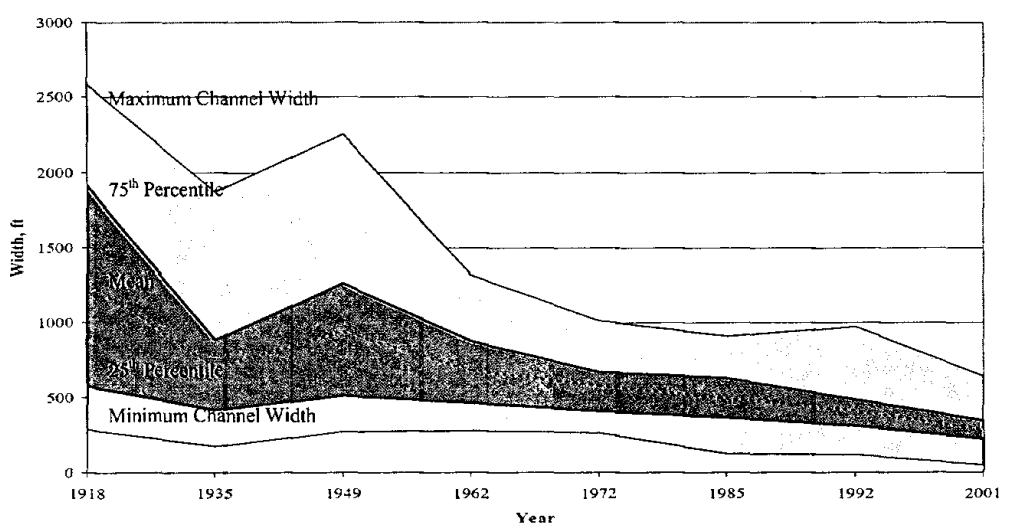


Figure 18. Channel width statistics over time for Middle Rio Grande between Angostura Diversion Dam and Bernalillo.

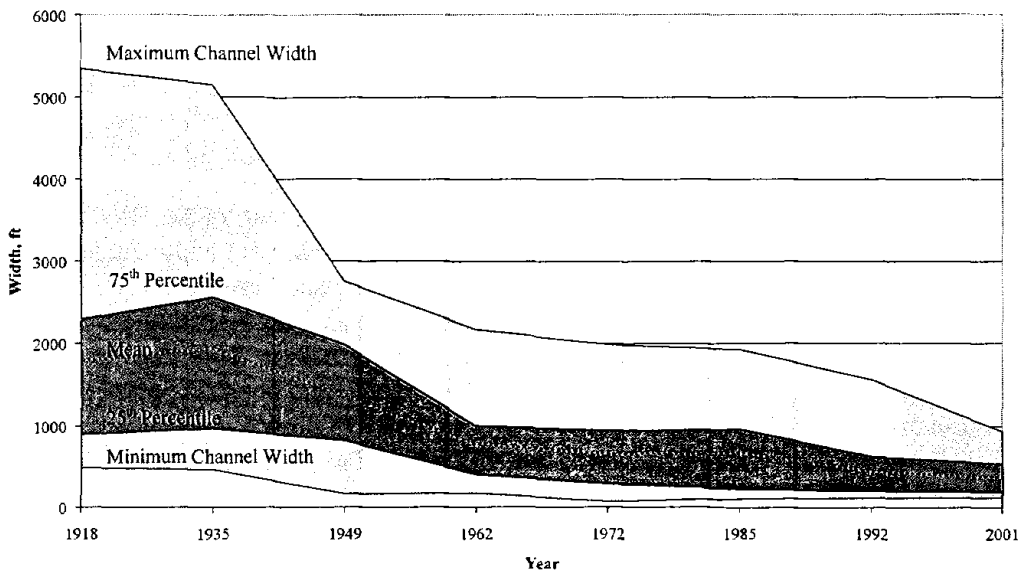


Figure 19. Channel width statistics for Middle Rio Grande between the Rio Puerco and San Acacia Diversion Dam.

Another area that has some unusual trends is between Arroyo de las Canas and the Highway 380 Bridge (river mile 95 – 87). As seen in Figure 21, this sub-reach had a large decrease in maximum channel width between 1918 and 1935. The maximum width decreased by over half (2,300 feet) while mean channel width decreased slightly (400 feet). Examination of GIS data and photographs suggest that most of the shift between 1918 and 1935 is due to a new channel location that is upstream from the Highway 380 Bridge. When main channel limits are compared, the 1935 and 1918 channels are similar except for the abrupt change near the bridge (see Figure 20). In 1918, the channel follows a large meander upstream and east of the bridge. By 1935, the meander bend has been abandoned and the channel follows a much straighter path.

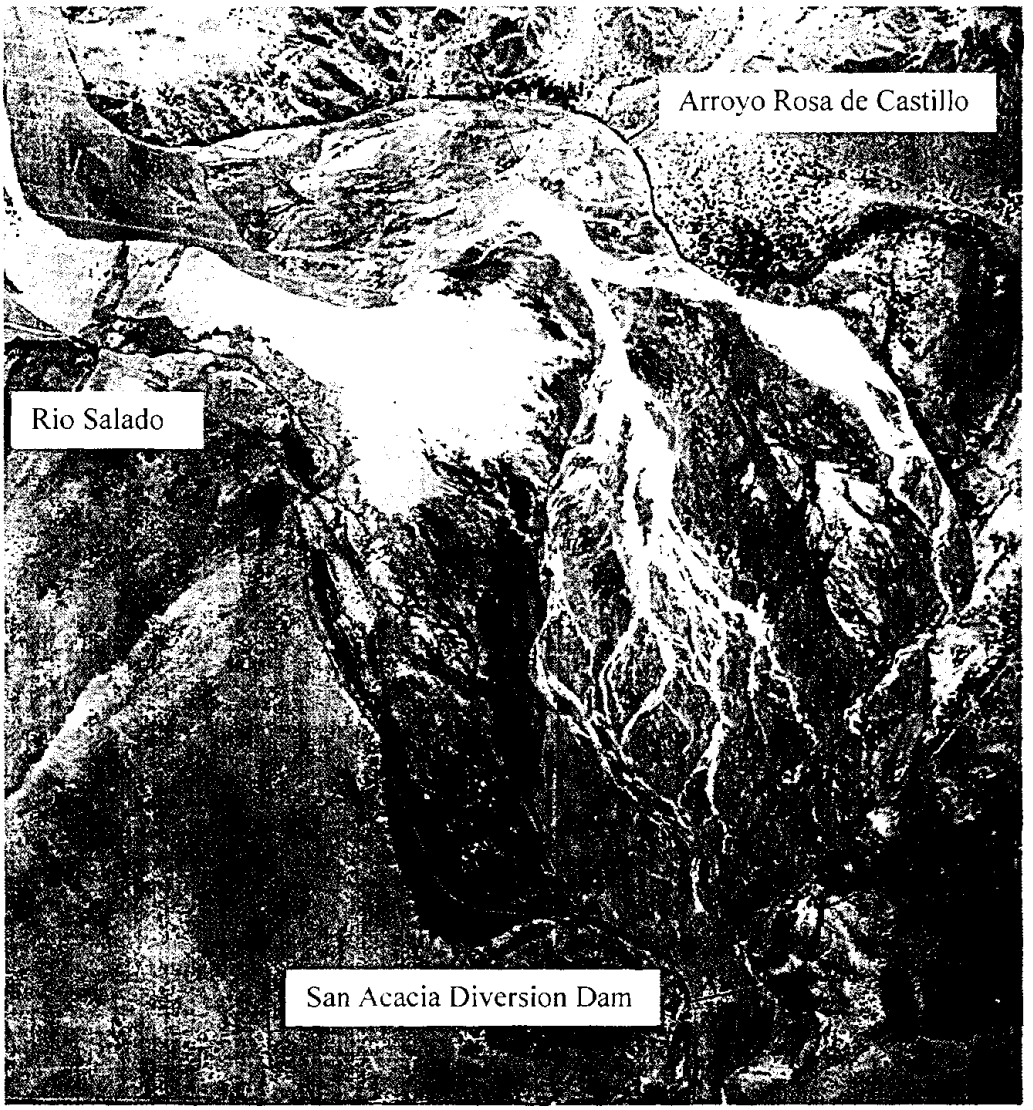


Figure 20. Sediment deposition upstream from San Acacia Diversion Dam in 1935.

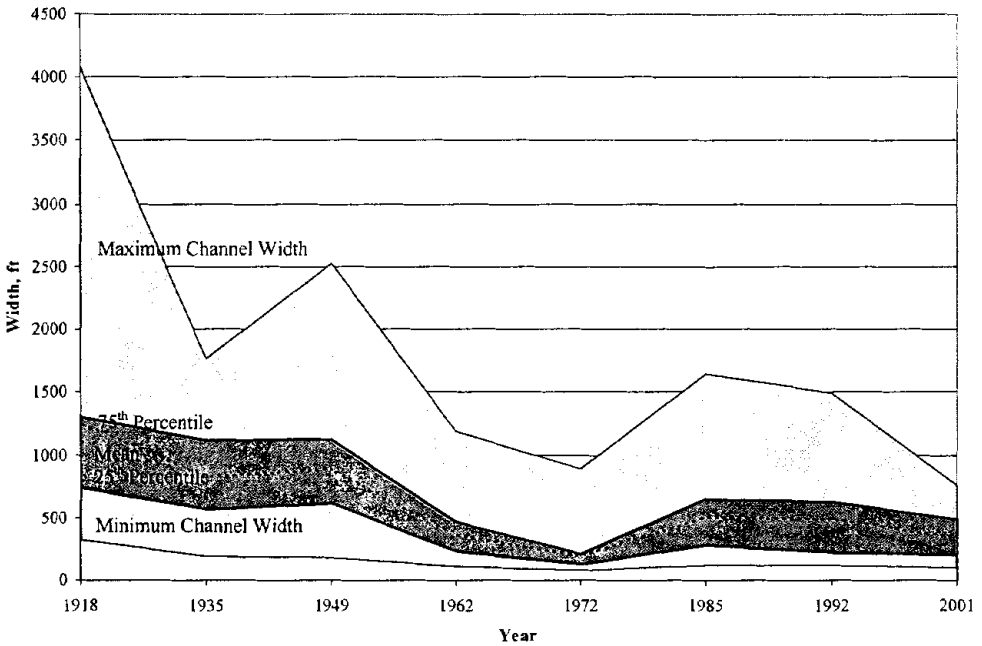


Figure 21. Channel width statistics for Middle Rio Grande between Arroyo de las Canas and Hwy 380.

Figure 23 shows the cumulative width of cross sections for the study reach. Some of the same trends discussed above can be seen in this single mass curve plot. Cross-section widths in 1918 were much wider than widths for other years. In addition, all data show a slope break near agg/deg 1600 (river mile 78). The flatter slope indicates that this part of the study reach has always been narrow during the study period. A general decrease in width between 1918 and 1949 can also be seen in this plot. There is very little difference between widths in 1935 and 1949 upstream of the Albuquerque area (agg/deg 19 – 450). Downstream of agg/deg 470, the curve flattens because the channel widths in 1949 are narrower. The cumulative width curve downstream of agg/deg 1600 is also flatter in 1949 than 1935 indicating narrowing in this period. Between 1949 and 1962, the cumulative width continued to decrease. The mass curve for 1962 has a flatter slope, particularly between range lines 300 and 1200. Much of this area, roughly between Bernalillo and San Acacia, was channelized with jetty jacks in the 1950s. The relatively constant slope of this section indicates that the channel widths were fairly uniform. Downstream of San Acacia Diversion Dam, the slope increases indicating an increase in channel width. The increase in channel width continues into the Bosque del Apache National Wildlife Refuge (agg/deg 1512 – 1637), to approximately river mile 78 where the river was diverted into a constructed channel on the east side of the valley in the 1950s.

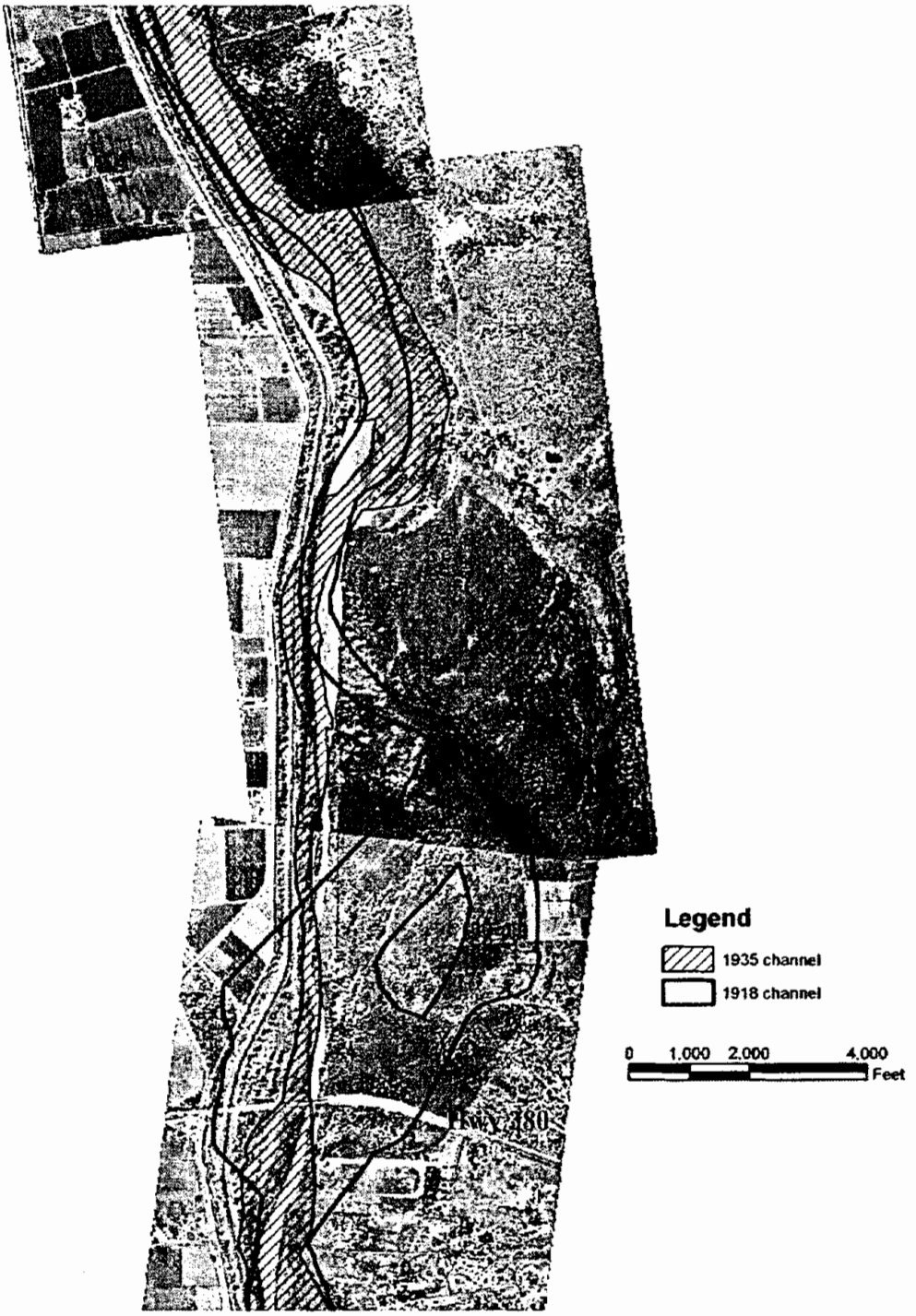


Figure 22. Aerial view of the 1918 and 1935 channels near the Highway 380 Bridge.

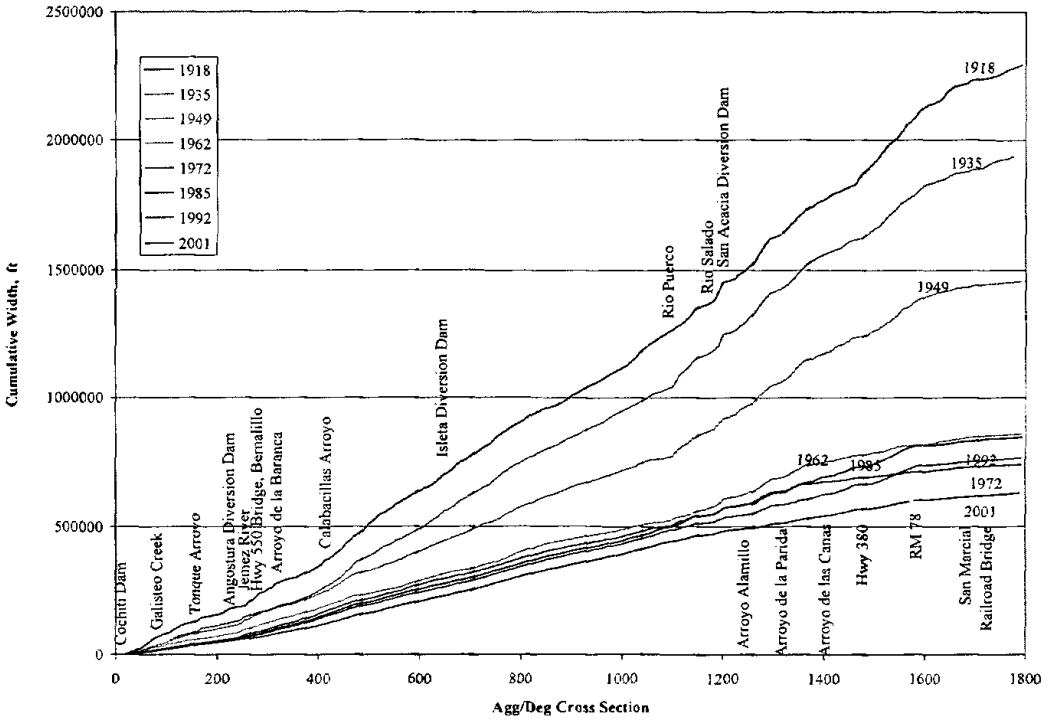


Figure 23. Cumulative channel cross section widths between Cochiti Dam and Elephant Butte Reservoir.

After 1962, cumulative channel widths decrease slightly. In 1972, the section between Bernalillo and San Acacia seems relatively uniform. Downstream from Arroyo de las Canas, channel widths in 1972 are much narrower and uniform as the mass curve follows a very flat slope. Aerial photography shows that much of this section of river was channelized in 1972. Channelization included clearing the floodway and excavating a narrow channel. The mass curve for 1985 indicates channel widening between Arroyo de las Canas and river mile 78. The slope angle continues past the 1972 break as if the river had not been channelized. Cumulative widths for 1992 are smaller than in 1985, but follow the same pattern as 1985. The decrease in cumulative width may indicate a general decrease in channel width rather than an abrupt change. Cumulative widths continue to change, 2001 widths are less than 1992 widths. Between Calabacillas Arroyo and San Acacia the difference in cumulative width is relatively constant; both years appear to have the same slope. Downstream from San Acacia, the difference is more pronounced and the slope of the 2001 mass curve decreases until it reaches river mile 78. At this point, the slope is similar to that of the previous data. The reduced slope of the mass curve between San Acacia and river mile 78 indicates channel narrowing in this reach.

The reach between Cochiti Dam and the Jemez River is particularly interesting. The cumulative width curves remained nearly constant from 1972 to 2001. If Cochiti Dam had a large impact on width adjustment, there should be a noticeable difference between

the 1972 and later data, which is not evident. It appears that major width adjustment in this reach had occurred by 1962.

6. Conclusions

Narrowing of the Rio Grande has resulted from natural processes such as the response to large floods and drought but also has been influenced by anthropogenic modifications including dam construction, river diversions, channelization, and vegetation removal. On rivers like the Rio Grande, channel characteristics are often determined by major flood events (Knighton, 1998). These large events are followed by many years of adjustment, which may include narrowing, incision, and the formation of vegetated islands and bars.

Vegetation plays an important role in width adjustment on the Rio Grande. Once established, vegetation anchors deposited sediments and makes lateral adjustment difficult unless certain thresholds such as shear stress levels or root strength are exceeded. One such example of this is documented by Lagasse (1980). After Cochiti Dam was constructed, there were several years without a bankfull discharge. The relatively low flows allowed vegetation to establish and contain the river into a low flow pattern. When flows finally came up, the river remained in the low flow pattern until a threshold was exceeded and the river returned to a straighter, high-flow pattern. Portions of the Socorro area show channel widening between 1972 and 1985. During the drought years, much of the floodway was cleared of vegetation. When higher flows returned, the channel was able to mobilized the bank sediments and widen up to the vegetation line. After the floodway clearing was stopped, the channel began to narrow as vegetation began to grow on islands and bars that were not scoured clear.

Photography from 2001 and 2002 shows that the development of well established islands has increased in recent years. With uninterrupted and continued development of islands, the wetted channel width will continue to decrease. Eventually, the islands may become attached to the river bankline or alternatively create an incised, anastomosed channel condition. The resulting river is likely to have narrow, high velocity, degraded channel(s) with a slightly increased meandering planform. If the channel incises to a significant degree and floods remain around 5,000 ft^3/s, the floodplain in many sections may become abandoned.

Speculation!

In summary, two main factors contributed to the river morphology changes shown by the data in this report. The first was changes in hydrology. The dry periods during the 1940s through the 1970s and after 1995 decreased the amount of water available in the basin. The second factor overlaps natural hydrology with anthropogenic activities. Flood control dams changed the timing and magnitude of upstream peaks. Dams and diversions changed sediment and discharge relationships. Canals and drains limited the flood plain area with levees. Channelization and bank stabilization narrowed the active channel. Both people and climate have caused planform characteristics of the Rio Grande to change over the years.

7. References

Abram Aerial Survey Corporation (1962). Middle Rio Grande Project - Photogrammetry, Aggradation/Degradation Rangelines, prepared for U.S. Bureau of Reclamation and U.S. Corps of Engineers under contract No. (Unknown), Lansing, Michigan.

Graf, (1994). *Plutonium and the Rio Grande, Environmental Change and Contamination in the Nuclear Age*, Oxford University Press, New York, New York.

Helsel, D. R. and Hirsch, R. M. (1992). *Statistical Methods in Water Resources*, Elsevier, Amsterdam, Netherlands, 522 pp.

Hereford R. (2002) Valley-fill alluviation during the Little Ice Age (ca. A.D. 1400-1880), Paria River basin and southern Colorado Plateau, United States. *GSA Bulletin*, v.114, no.12, p 1550-1563.

Knighton, D., (1998). *Fluvial Forms and Processes*. Arnold, London, England. 383 pp.

Lagasse, P. F., (1980). An Assessment of the Response of the Rio Grande to Dam Construction-Cochiti to Isleta. A Technical Report for the U.S. Army Corps of Engineers. Albuquerque, New Mexico.

Lane, E.W., (1955). Design of stable channels. *Transactions of the American Society of Civil Engineers*, 120, p 1234-1260.

Makar, P.W. and R.I Strand, (draft 2002a). Geomorphological Assessment of the Rio Grande: Escondida Bridge to near Fort Craig, New Mexico. U. S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO

Makar, P.W. and R.I Strand, (draft 2002b). Geomorphologic Responses of the Middle Rio Grande: San Acacia to Elephant Butte. U. S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, Denver, CO

Massong, T., T. Bauer, and M. Nemeth, (2003). Geomorphic Assessment of the Rio Grande San Acacia Reach, U.S. Bureau of Reclamation report, River Analysis Team, Technical Services Division, Albuquerque, NM.

Oliver K.J., (2004). Planform interpretation of the Rio Grande from Velarde to the Narrows of Elephant Butte – Geographic Information Database of the Historic River Channel for 1908 - 2001. U. S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Remote Sensing and GIS Group, Denver, CO.

Richard, G., C. Leon, and P.Y. Julien, (2001). Hydraulic modeling on the middle Rio Grande, New Mexico, Rio Puerco reach. Unpublished U.S. Bureau of Reclamation

report, River Analysis Team, Technical Services Division, Albuquerque, NM.

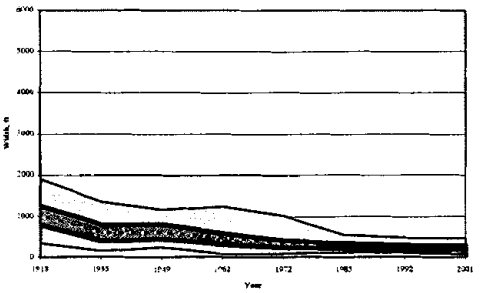
Schumm, S.A., (1969). "River Metamorphosis," *J. Hydraulic Div*. ASCE, 95(HY1), Paper 6352, pp. 255-273.

Scurlock, Dan, (1998). *From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin.* Rock Mountain Research Station. Fort Collins, Colorado.

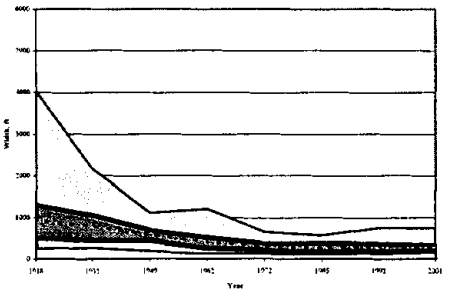
APPPENDIX A Width Variability of Subreaches

Width variability within short subreaches is presented in the following graphs. The graphs are similar to Figures 11- 17 and 19 in the main text where the top line is maximum width and bottom line is minimum width. Central dark area is the central 50% of width values. The center dotted line is the mean width of the subreach.

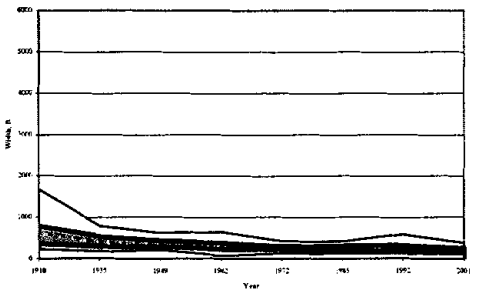
Subreach 1 - Cochiti to Galisteo Cr.



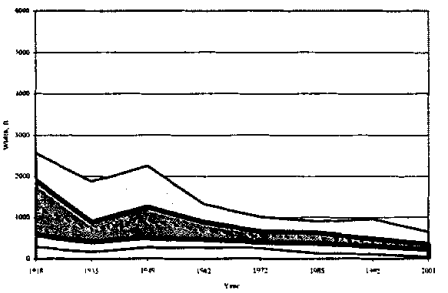
Subreach 2 - Galisteo Cr. to Tesque Ar.



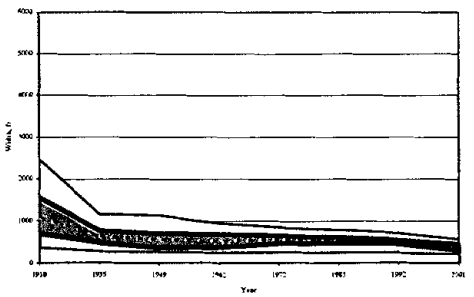
Subreach 3 - Tesque Ar. to Angostura



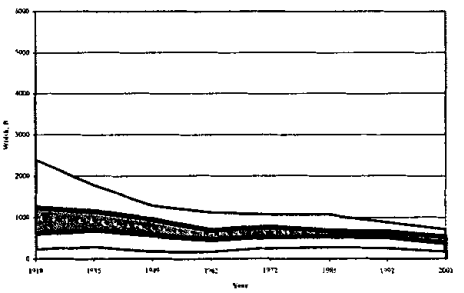
Subreach 4 - Angostura to Bernalillo



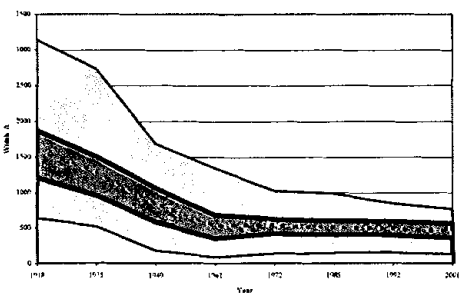
Subreach 5 - Bernalillo to Ar. de la Barranca



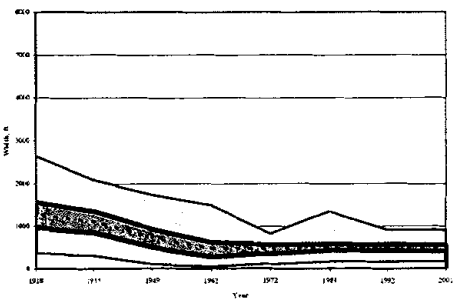
Subreach 6 - Ar. de la Barranca to Calabacillas Ar.



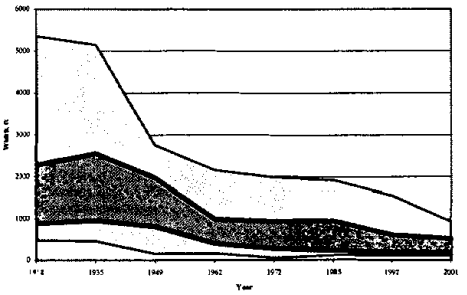
Subreach 7 - Calabacillas Ar. to Isleta DD



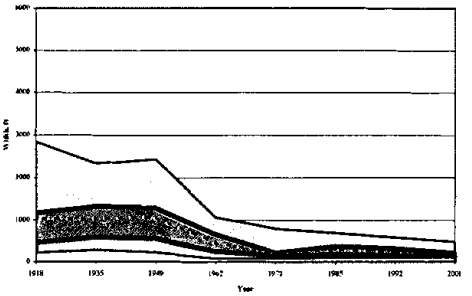
Subreach 8 - Isleta DD to Rio Puerco



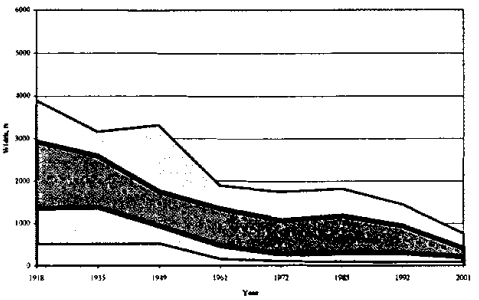
Subreach 9 - Rio Perro to San Acacia DD



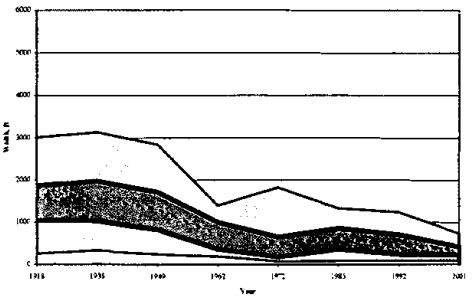
Subreach 10 - San Acacia DD to Ar. Alamillo



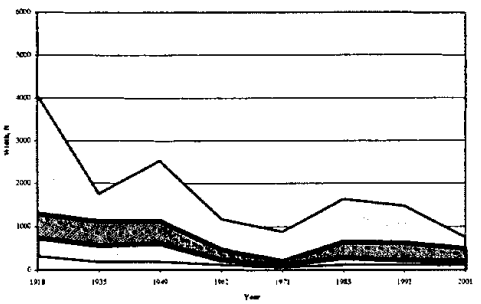
Subreach 11 - Ar. Alamillo to Ar. de la Parida



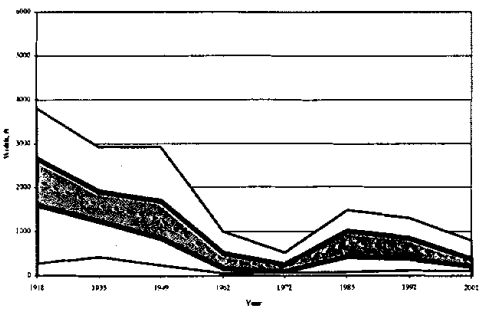
Subreach 12 - Ar. de la Parida to Ar. de las Cruces



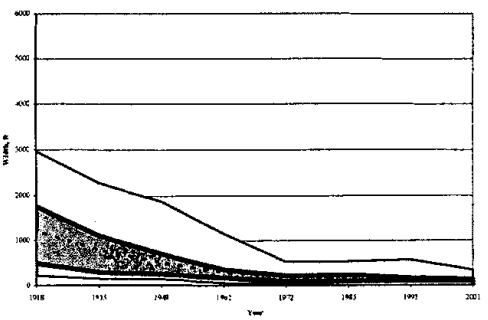
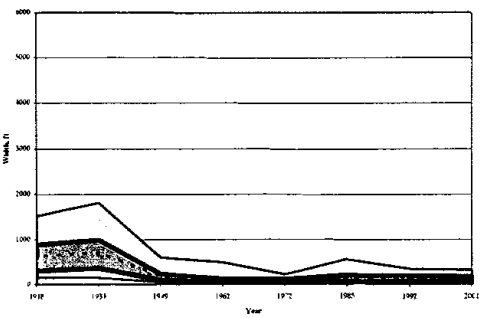
Subreach 13 - Ar. de las Cruces to Hwy 380



Subreach 14 - Hwy. 380 to RM 78



Subreach 15 - RM 78 to San Marcial RR



Subreach 16 - San Marcial RR to Sta. 1800