# APPENDIX B

## Preliminary Geomorphic Assessment of the Bernalillo-Albuquerque Reach

Middle Rio Grande near Albuquerque, New Mexico
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## Introduction and Background

To better understand the long-term effects of dam operations and other anthropogenic and natural influences on the middle Rio Grande, the Bureau of Reclamation has provided funding for a geomorphic study of a 25 km reach from the US 550 bridge in Bernalillo downstream to the Montano Street bridge in north Albuquerque (Fig. 1). The Rio Grande drains more than 273,530 km$^2$ of the southwestern United States and Mexico, with about 37,555 km$^2$ of the basin directly contributing to the flow of the river through the study reach. The river flows from the San Juan Mountains of southern Colorado to the Gulf of Mexico more than 3000 km away (Collier et al., 1996) (Fig. 2). Through New Mexico, the Rio Grande flows through a series of continental rift grabens partly filled with Cenozoic alluvial fan deposits, related piedmont deposits of the Santa Fe Group (Bachman and Mehnert, 1978; Lambert, 1968; Dethier, 1999), and Cenozoic and modern fluvial sediments (Connell, 1998). The Middle Rio Grande Valley begins at the southern end of White Rock Canyon, southwest of Santa Fe, and extends south for about 230 km to the San Marcial constriction (Lagasse, 1980; Baird and Sanchez, 1997).

Around 1925, various state and federal agencies began to constrain and channelize the river through the use of various methods. The first of these methods were the construction of diversion dams and flood control levees placed parallel to the river. The Middle Rio Grande Conservancy District controls these levees and diversion dams (Lagasse, 1994). Between 1953 and 1973, the Corps of Engineers constructed one main-stem dam at Cochiti and 3 tributary dams: Abiquiu on the Chama River (~ 80 km above

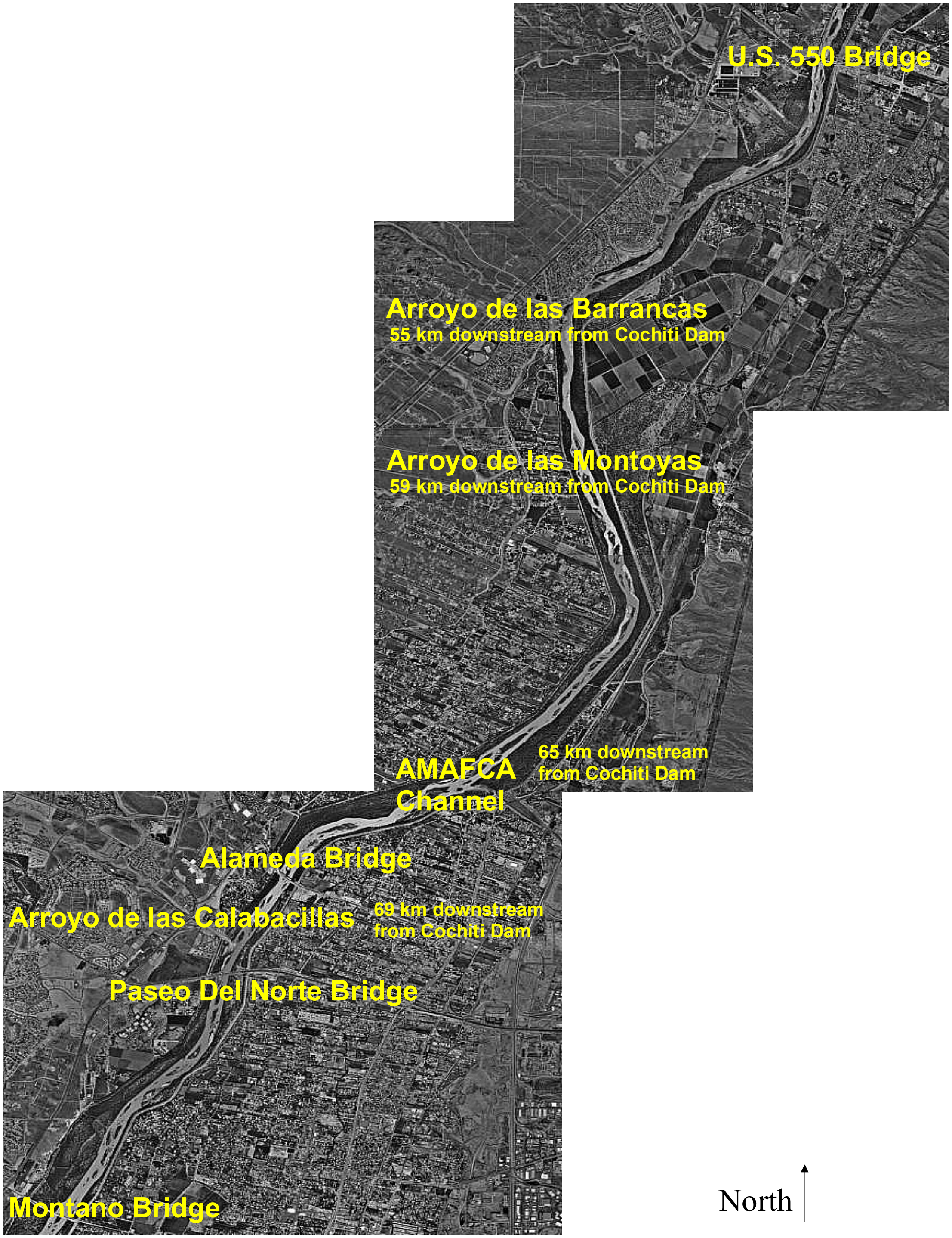


Figure 1. Entire study reach from U.S. 550 Bridge in the north to Montano Rd Bridge in the south. Length of reach is 25 river kilometers. Resolution is 16 m. Air photos courtesy of USGS.

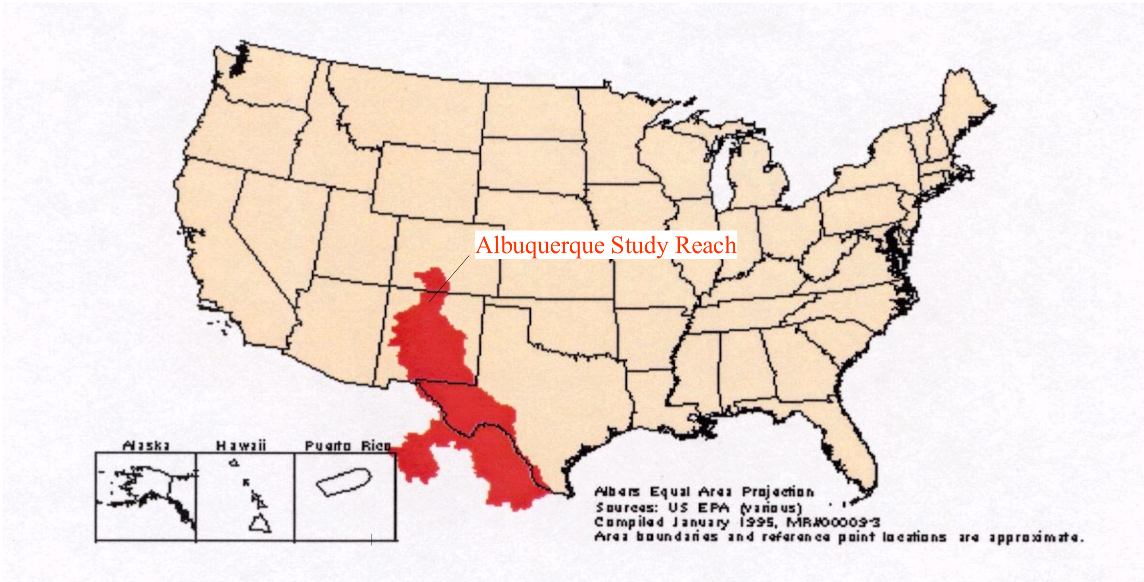


Figure 2. The extent of the Rio Grande drainage basin in the southwestern United States and northern New Mexico. Image from US Environmental Protection Agency (www.epa.gov).

Figure 3. Photo of Kellner Jetty Jacks along the eastern bank of the Rio Grande. Banks have remained stable since jetty jack instalation during the late 1940s to early 1950s

Cochiti), Galisteo on Galisteo Creek (12.8 km below Cochiti), and Jemez Canyon on the Jemez River (35.4 km below Cochiti). These dams were built to work in conjunction with the levees to provide flood control to the Middle Rio Grande Valley. In addition to the work performed by the Middle Rio Grande Conservancy District and the Corps of Engineers, the Bureau of Reclamation installed Kellner jetty jacks extensively along the study reach (Fig. 3). These permeable steel structures were used to trap sediment and stabilize the banks of the river with the help of natural vegetation (Lagasse, 1981).

Prior to dam construction, the middle Rio Grande channel contained many unvegetated bars and islands, with bed sediment comprised primarily of fine and medium sands and lesser pockets of gravel. It has been estimated that ~80% of sediment inflow to the middle Rio Grande is now trapped by Cochiti, Jemez Canyon, and Galisteo dams, with Cochiti alone receiving ~$2.2 \times 10^6$ $m^3$ of sediment a year (Lagasse, 1994, Baird and Sanchez, 1997). A 31-year pre-dam record and a 23-year post-dam record of discharge data at the Central Bridge gauge in Albuquerque show that peak discharges below Cochiti have not changed markedly, the primary difference being the lack of large flood flows greater than 283 $m^3/s$ (10,000 $ft^3/s$) (Fig. 4). A longer pre-dam record (Fig. 5) indicates that peak discharges in the 31-year pre-dam period are relatively low compared to earlier peak flows dating back to the late 1860s (Kelley, 1982), however, the original source and reliability of these older data are unclear. The channel bed began to degrade and become coarser and locally armored below Cochiti Dam shortly after its closure (Lagssse, 1980; Williams and Wolman, 1984). A transition zone between the coarsened bed of pebble and cobble gravels and a fine to medium sand bed similar to pre-dam conditions migrated downstream at an initial rate of ~5 km/yr, but this rate has slowed

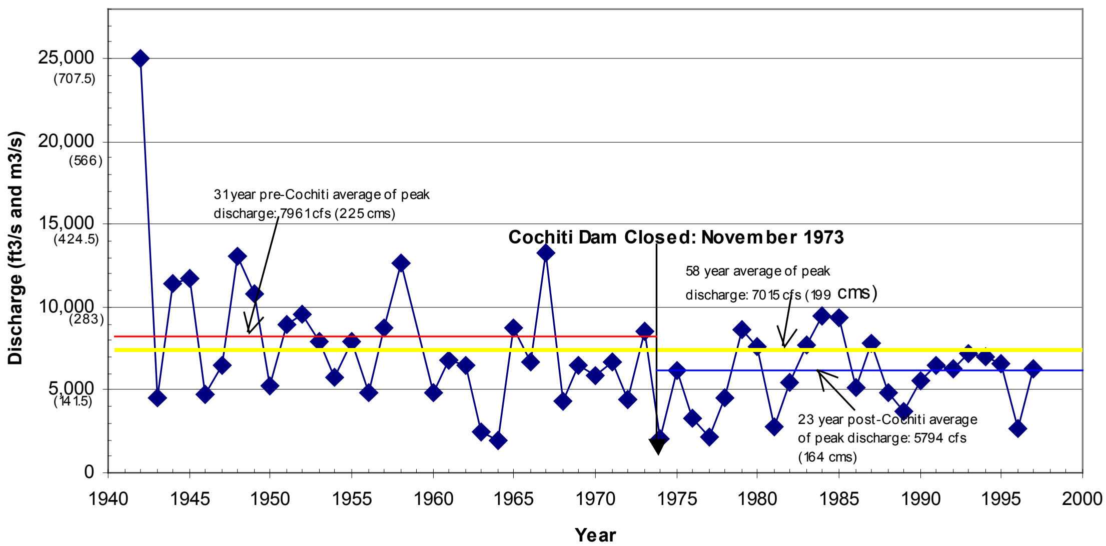


Figure 4. Plot of the annual peak discharges for the 58 year USGS gage record of the Rio Grande at Albuquerque (gage ID: 08330000). Lines indicate the average discharge for the entire record, as well as pre and post-Cochiti average discharges.

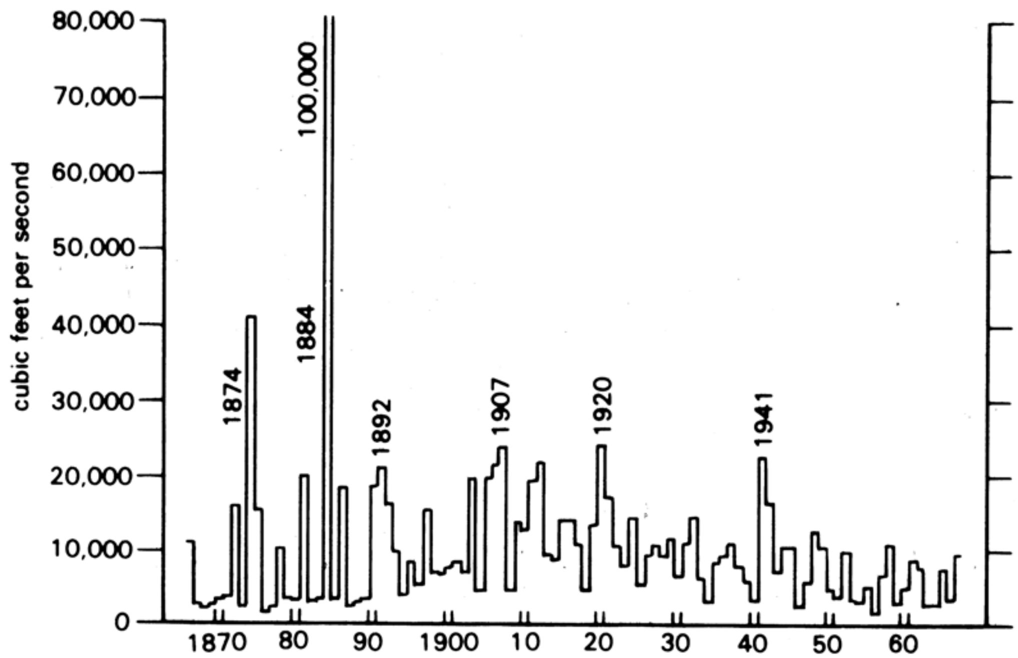


Figure 5. Pre-dam peak discharge record for the Rio Grande from the middle 1860's to the late 1960's. Discharges are measured in cubic feet per second (10,000 ft³/s = 283 m³/s) (from Kelley, 1982).

over the last 30 years, likely in part because of sediment inputs from major tributaries downstream, including Galisteo Creek, Arroyo Tonque, the Jemez River, and Arroyo de las Barrancas (Lagasse, 1981).

Located directly north of Albuquerque, New Mexico, the study reach extends 25 km from U.S. Highway 550 in Bernalillo, NM downstream into Albuquerque to the Montano Street Bridge. The active channel within the study reach varies dramatically along the 25 km. In the upstream reach, the low-discharge channel width is typically between 20 and 30 m and dominated by a deeply incised thalweg that forms a single channel at low flows, with only a locally island-braided planform. In the downstream section of the study reach the channel is relatively uniform at about 100 m width, with a shallow, multi-threaded, island- and bar-braided planform. Channel incision over the last 30 years has created an elevated and abandoned floodplain along the entire length of the study reach. Net channel incision measured from 1972 bed elevations from within the reach ranges between about 2.5 m in the upstream reach to 1.2 m downstream (Fig. 6). The floodplain is heavily vegetated with cottonwood, saltcedar, Russian olive, and Siberian elm (Milford et al., 2003), and was last flooded significantly in the early 1940s. Currently, bed sediment along the study reach ranges from cobbles to fine sand, with gravel dominant in upstream reach and medium to coarse sands dominant downstream.

Four major tributaries enter the Rio Grande within the study reach (Fig. 1). Three of these tributaries drain the northern Llano de Albuquerque to the west of the river, whereas the fourth drains the Sandia Mountain front and northeastern Albuquerque and enters from the east. The three western arroyos are the Arroyos de las Barrancas, Montoyas, and Calabacillas, which drain areas underlain by erodible Santa Fe Group

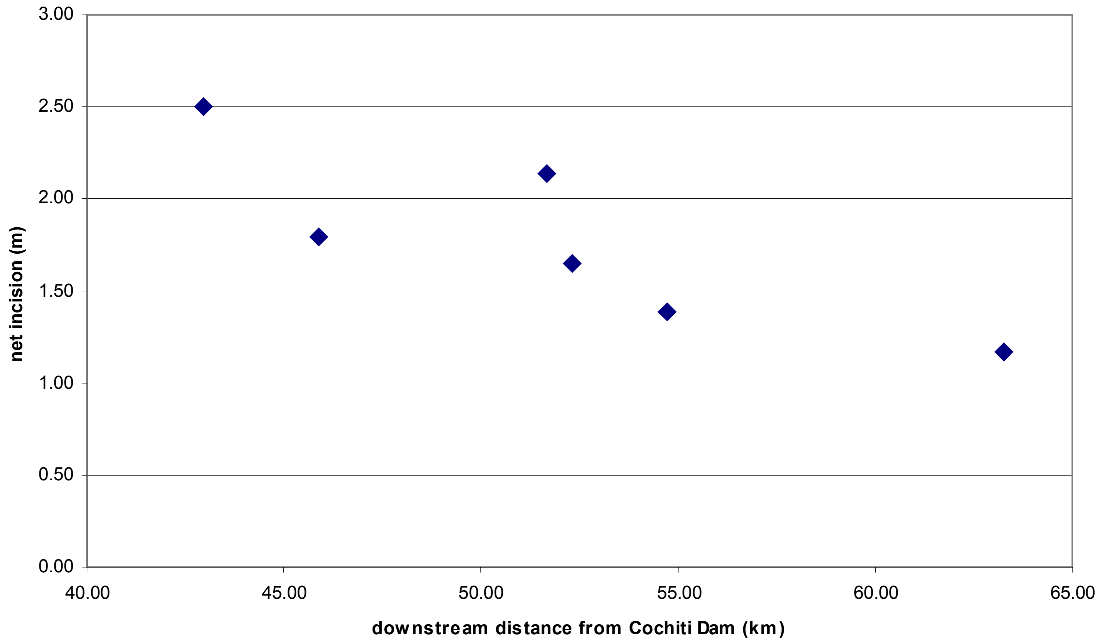


Figure 6. Net incision of study reach downstream from Cochiti Dam. Differences between 1972 average bed elevation and 2001 average bed elevation at Bureau of Reclamation cross-section lines were calculated to determine amount of net incision.

sediments that can supply abundant sand and lesser gravel (e.g., Connell, 1998). The largest of these tributary basins is the Calabacillas drainage, which is about 220 $km^2$ (Hawley and Wells, 1991). Arroyo de las Barrancas enters approximately 56 km downstream from Cochiti Dam, and its drainage basin is about 1/3 the size of the Calabacillas drainage area. A substantial fan deposit and downstream gravel bar is present at its confluence with the Rio Grande (Lagasse, 1981). The channel has been extensively modified upstream with erosion and flood control structures. Arroyo de las Montoyas enters ~59 km downstream from Cochiti Dam, and its drainage basin is approximately ½ the size of the Calabacillas drainage area. The lower arroyo is straightened and concrete-lined through the town of Corrales to the Rio Grande. Arroyo de las Calabacillas is located approximately 69 km downstream from Cochiti Dam. The Calabacillas arroyo has formed a natural fan deposit at its confluence with the Rio

Grande, but just west of the confluence the arroyo channel has been extensively engineered. The AMAFCA North Diversion Channel is the only significant tributary within the study reach that enters from the east. This channel is part of a largely engineered network of drainage and flood control structures, although some potential sediment sources exist along the Sandia Mountain front. The mouth of the channel is heavily engineered with no observed fan formation, although the Rio Grande channel is unusually wide in the confluence area. The mouth of the channel is located approximately 65 km downstream from Cochiti Dam.

The primary purposes of this study are to (1) describe the transition zone between the upstream narrow, incised, and coarsened reach, and the downstream broader sand-bed reach; (2) investigate its development and migration since the closure of Cochiti Dam; and (3) understand controls on the downstream progression of the dam effects. Previous work on this transition zone within the Rio Grande channel was conducted by Lagasse (1981), who documented its development shortly after the closure of Cochiti Dam. Since this time, however, no specific work has been completed in order to better understand post-dam changes within the Bernalillo to Albuquerque reach.

Within the Middle Rio Grande Valley, the Bureau of Reclamation and the Corps of Engineers consider discharges above 142 $m^3/s$ to be channel-forming flows, based on the 1.5-year recurrence interval discharge and field evidence (Tamara Massong, Bureau of Reclamation, pers. comm.). Studies performed by the Bureau of Reclamation and the Corps of Engineers for the "Rio Grande Comprehensive Plan", indicated that pre-Cochiti Dam channel-forming flows for the Middle Rio Grande were around 170 $m^3/s$ (Schembera, 1963).

## Methods

Data collected for this study includes grain size analysis from sediment samples collected along the length of the reach, sand depth measurements from within the active channel, bank and vegetated island sediment descriptions, island area changes, and a water surface profile.

*Particle-size Analysis*

Bed sediment grab samples were collected along the length of the study reach to obtain a representative sampling of bed sediment variation. Individual sample collection was focused on the active channel of the river including the banks, thalweg, sandbars, and smaller sub-channels that branched off the thalweg. The following methods were used for the grain size analysis: Following desiccation, a sample splitter was used to obtain about 100 grams of sample, weighed to 0.01 g. Using a standard set of sieves with an interval of 0.5 $\phi$, the sample was sieved for 15 minutes in a Ro-Tap shaker. Individual sieve fractions were weighed and entered into a spreadsheet to calculate distribution of grain sizes. Using the cumulative distribution curves created in the spreadsheet, median grain size ($D_{50}$) values were determined and reach-wide and sub-reach grain-size plots were created.

*Bed Sand-depth Measurements*

Sand depths from within the active channel of the study reach were measured using a 1.5-meter length of rebar, the maximum practical length. The site locations were chosen to represent within-reach variations, from within the thalweg to emergent sandbars. The rebar was hammered into the sandy sediment and when resistance became significant in hard sediments, it was assumed that a gravel deposit was encountered, and a sand depth was recorded. In areas where little resistance was encountered and the rebar was hammered completely into the sediment, a depth of greater than 1.5 m was recorded.

*Bank Sediment Descriptions*

Initial reach-wide field observations of bank sediments revealed a relatively uniform sandy character to the main east and west banks. Island banks showed more variability and some gravel content. Detailed bank and vegetated island descriptions were obtained at four locations along the length of the study reach. This work included generalized descriptions of sediment sizes and distributions within the exposure as well as unit thickness. Sedimentary structures, if any, were also recorded along with the distribution of root fragments.

*Vegetated Island Area*

Vegetated island areas were measured from GIS shape files from air photos provided by the Bureau of Reclamation for the years 1972, 1985, and 1992, and shape files created by the author for this project using the 2001 digitized air photos of the study reach. The vegetated islands were traced and converted into a coverage using ArcInfo, which allowed area calculations to be compared with the area measurements from the Bureau of Reclamation files. I followed the procedure used by Bureau of Reclamation personnel, who traced the vegetated perimeter of islands visible on the air photos to create the shape files. This same protocol was used during the creation of the island shape files for this project.

A water surface profile was surveyed along the length of the study reach. This work involved use of an automatic level and 3-meter stadia rod to measure elevations, and a real-time differential GPS system with submeter accuracy for map locations. Because of the lack of accessible benchmarks at the starting point of the survey (Bernalillo Bridge), an arbitrary datum with elevation of 100 m was established at a stable temporary benchmark on a bridge abutment for use during the survey. Future work will tie the survey into known benchmarks at Alameda Bridge and downstream locations. Survey work was conducted at discharges of about 1100 cubic feet per second ($ft^3/s$) (31 $m^3/s$) for the upstream part of the profile and 800 $ft^3/s$ (23 $m^3/s$) for the downstream part. Distances between survey points ranged from approximately 50 m to more than 300 m. Elevations were corrected for Earth curvature and refraction effects. The survey generally followed the primary thalweg of the river, and point-to-point distances were calculated. Water surface slopes were also calculated between survey points, and general slopes of subreaches were estimated using standard linear regression.

## Results

### *Floodplain and terrace observations*

Although Holocene and historic terraces are observed along some reaches of the Middle Rio Grande (Massong et al. 2000), GPS mapping and field observations in the study reach revealed only a single young floodplain surface. This surface was constructed by aggradation within the levees since their construction, aided by deposition around jetty jack lines. It is also commonly higher than the adjacent floodplain outside the levees by about 1.5 m. The overall Holocene trend of vertical channel change in this reach has been aggradation, as indicated by approximately 70 feet of Holocene fluvial sediments observed in auger holes at Bernalillo Bridge (Connell, 1998; B. Allen, New

Mexico Bureau of Geology and Mineral Resources, pers. comm., 2003). Deposition on the floodplain surface in most places last occurred in the early 1940s with the last high discharges through this reach. The floodplain is now elevated and is essentially a historic terrace because of channel incision. No higher historic or Holocene terraces were observed along this reach. Large, high, side-attached gravel bars along the upstream reach may ultimately become abandoned as terraces, however, if channel incision continues and along with flow regulation prevents flooding on their surfaces.

High fluvial terraces of probable late Pleistocene age flank the west bank of the Rio Grande along parts of the upstream reach, and their associated deposits were mapped as the Los Duranes formation by Connell (1998). These are potential minor sources of gravel to the Rio Grande channel, as described with bank sediments below.

*Bed Sediment Size Variations*

A total of 104 bed sediment samples were collected along the length of the study reach. Sediment size terminology used here follows the Wentworth classification (Table 1). Sampling was particularly focused in and around the apparent transition zone between pebble and cobble gravel bed sediments (2-128 mm) dominant in the upper reach and fine to coarse-grained sands (0.125-1 mm) in the lower reach (Fig. 7).

The coarsest bed sediments of medium cobbles (~128 mm) were located at the upstream end of the reach near U.S. 550, whereas the finest significant areas of the bed were very fine sands found around the Arroyo de las Montoyas. Median grain sizes throughout the reach range from 64 mm to 0.125 mm. The coarsest grained material ($D_{50}$ up to ~64 mm) is found in the upstream part of the reach. Downstream of Arroyo de las Barrancas median grain sizes become generally finer, but a gravel component ($D_{50}$ up to

| Millimeters | µm | Phi (ϕ) | Wentworth size class | |
|---|---|---|---|---|
| | | -20 | | |
| 4096 | | -12 | Boulder (-8 to -12ϕ) | |
| 1024 | | -10 | | |
| 256 | | -8 | | |
| 64 | | -6 | Cobble (-6 to -8ϕ) | |
| 16 | | -4 | Pebble (-2 to -6ϕ) | |
| 4 | | -2 | | Gravel |
| 3.36 | | -1.75 | | |
| 2.83 | | -1.50 | Granule | |
| 2.38 | | -1.25 | | |
| 2.00 | | -1.00 | | |
| 1.68 | | -0.75 | | |
| 1.41 | | -0.50 | Very coarse sand | |
| 1.19 | | -0.25 | | |
| 1.00 | | -0.00 | | |
| 0.84 | | 0.25 | | |
| 0.71 | | 0.50 | Coarse sand | |
| 0.59 | | 0.75 | | |
| 1/2 – 0.50 | 500 | 1.00 | | |
| 0.42 | 420 | 1.25 | | |
| 0.35 | 350 | 1.50 | Medium sand | Sand |
| 0.30 | 300 | 1.75 | | |
| 1/4 – 0.25 | 250 | 2.00 | | |
| 0.210 | 210 | 2.25 | | |
| 0.177 | 177 | 2.50 | Fine sand | |
| 0.149 | 149 | 2.75 | | |
| 1/8 – 0.125 | 125 | 3.00 | | |
| 0.105 | 105 | 3.25 | | |
| 0.088 | 88 | 3.50 | Very fine sand | |
| 0.074 | 74 | 3.75 | | |
| 1/16 – 0.0625 | 63 | 4.00 | | |
| 0.0530 | 53 | 4.25 | | |
| 0.0440 | 44 | 4.50 | Coarse silt | |
| 0.0370 | 37 | 4.75 | | |
| 1/32 – 0.0310 | 31 | 5 | | |
| 1/64 0.0156 | 15.6 | 6 | Medium silt | |
| 1/128 0.0078 | 7.8 | 7 | Fine silt | |
| 1/256 – 0.0039 | 3.9 | 8 | Very fine silt | |
| 0.0020 | 2.0 | 9 | | Mud |
| 0.00098 | 0.98 | 10 | | |
| 0.00049 | 0.49 | 11 | Clay | |
| 0.00024 | 0.24 | 12 | | |
| 0.00012 | 0.12 | 13 | | |
| 0.00006 | 0.06 | 14 | | |

Table 1. Wentworth grain size classification scale (from Wentworth, 1922)

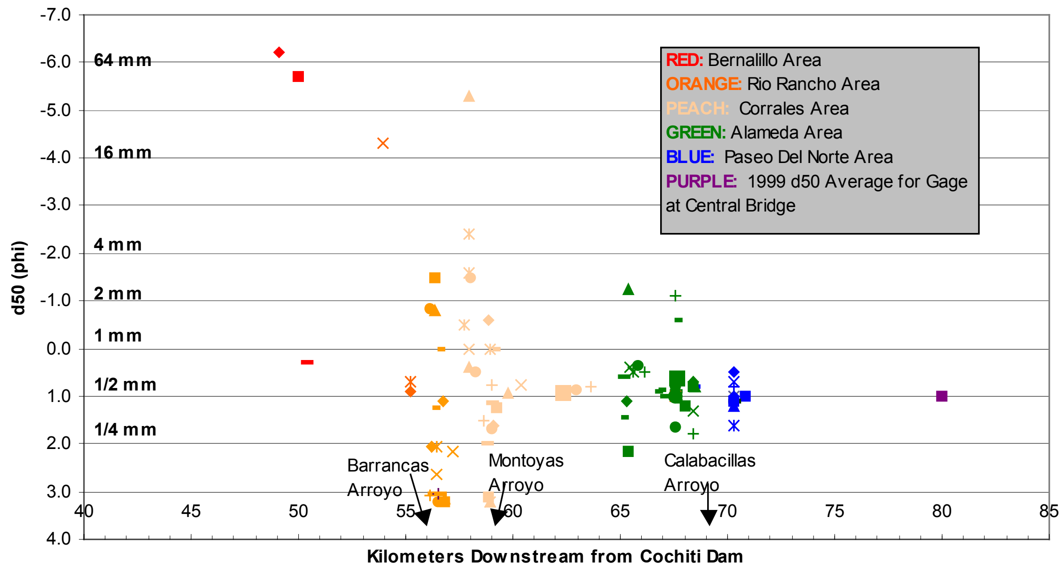


Figure 7. Median grain size values for study reach showing downstream fining trend and decrease in median size variability through transition zone between Arroyo de las Barrancas and Arroyo de las Montoyas. Grain sizes in the study reach range from fine-sands to large cobbles.

~32 mm) remains within the channel. Downstream of Arroyo de las Montoyas this fining trend continues but gravel is largely absent. The largest grain sizes sampled below Arroyo de las Montoyas are no larger than very coarse sand and granules (up to about 4 mm).

Another trend observed in the grain size data is a reduction in variability of median grain sizes within sub-reaches downstream. The most upstream sub-reach around the U.S. 550 Bridge has a range of median grain sizes from 1-64 mm, whereas the most downstream sub-reach south of Paseo del Norte has a range from 0.25-1 mm. Although the most upstream sample areas contain the coarsest grained material, the largest variability with the study reach occurs around the transition zone. Specifically, the areas of highest variability are found around the two major arroyos currently sampled (Fig. 7).

The most upstream of these tributary arroyos, Arroyo de los Barrancas, has a range of median grain sizes from 0.125-16 mm. Arroyo de las Montoyas has a wider range of median grain sizes, from 0.125-32 mm.

*Historical Sediment Size Changes*

Directly after closure of Cochiti Dam in 1973, the study reach experienced a coarsening of bed sediments from fine sand (average $D_{50}$ of 0.21 mm or 2.5$\phi$) to medium sand (average $D_{50}$ of 0.27 mm or 1.5$\phi$) (Fig. 8). This coarsening occurred prior to the gravel- to sand-bed transition zone reaching its current location within the study reach.

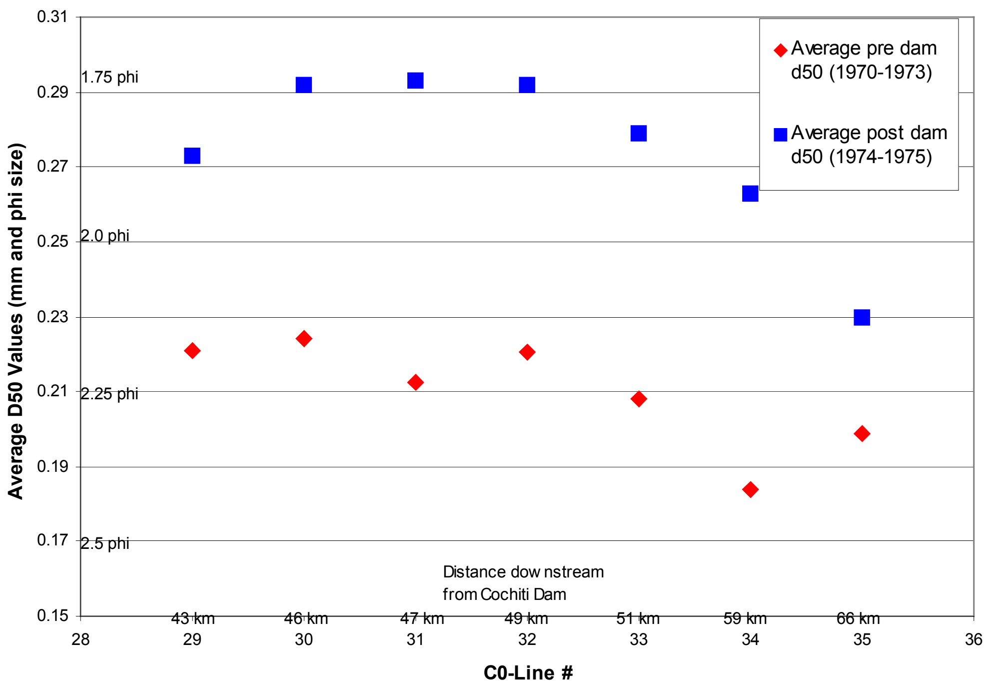


Figure 8. Plot showing the change in average median grain sizes of bed sediment within the study reach before and directly after closure of Cochiti Dam. CO-Line numbers correspond to Bureau of Reclamation repeated survey cross-section lines within the study reach. All samples on this plot are within the medium to fine-grained sand range.

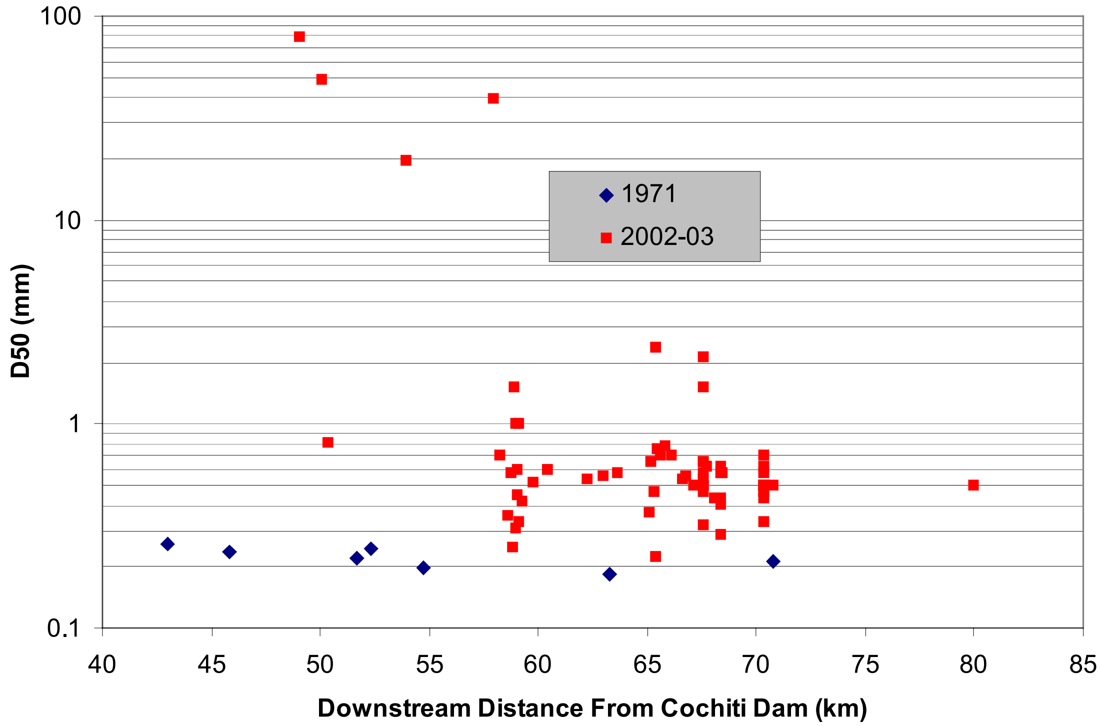


Figure 9. Variation in median grain size of bed sediments over the study reach in 1971 (pre-Cochiti dam) compared to those sampled in this study (2002-2003)

Comparison of averaged median grain size data collected in this study with historical data provided by the Bureau of Reclamation show that prior to dam closure, bed sediments were sand with little variability in median grain size throughout the reach (0.21 to 0.27 mm. Present downstream variation in median grain sizes is large (0.44 to 79 mm) (Fig. 9).

*Bed Sand Depths*

Sand depth measurements were taken at 13 locations along the study reach between U.S. 550 and Alameda Bridge. Along the length of the reach sand depths ranged from 25 cm to greater than 155 cm. The shallowest sand depths were measured in the upstream half of the study reach where depth ranged from 25 cm to greater than 155 cm.

Conversely, in the downstream half of the study reach all sand depths measured were greater than 155 cm (Fig. 10). The amount of channel area composed of sand deposits varied with distance downstream. Based on field estimates, the far upstream end of the study reach near U.S. 550 Bridge contained approximately 5-10% sand within the high-flow channels, and less than 5% sand within the active channel. The middle section of the reach around Arroyo de las Barrancas and Arroyo de las Montoyas was estimated to contain 30-60% sand within the active channel and high- flow channels. The most downstream section of the reach from Alameda bridge south to Montano bridge is estimated to contain greater than 95% sand within the active channel and high-flow channels, field observations indicate a much smaller proportion of the overall channel width consists of high-flow channels.

*Bank Sediments*

Field observations indicate that bank sediments along the main east and west banks consist mostly of fine to medium-grained sands with minor mud lenses along the entire study reach. The main exceptions to this are areas where the active channel has cut into Pleistocene terrace deposits along its western margin upstream of the Arroyo de las Barrancas. These ~5-15 m high terrace deposits consist primarily of sand to cobble gravel. Although the gravel deposits are only exposed in approximately 45 to 50 percent of terrace faces, the gravels make up about 10 to 25 percent of the exposed sediment in those locations.

Bank sediments are dominated by sand along most of the study reach, including in banks of vegetated islands. Units of pebble and cobble gravel, however, are commonly found within the vegetated island sediments in the upstream part of the reach.

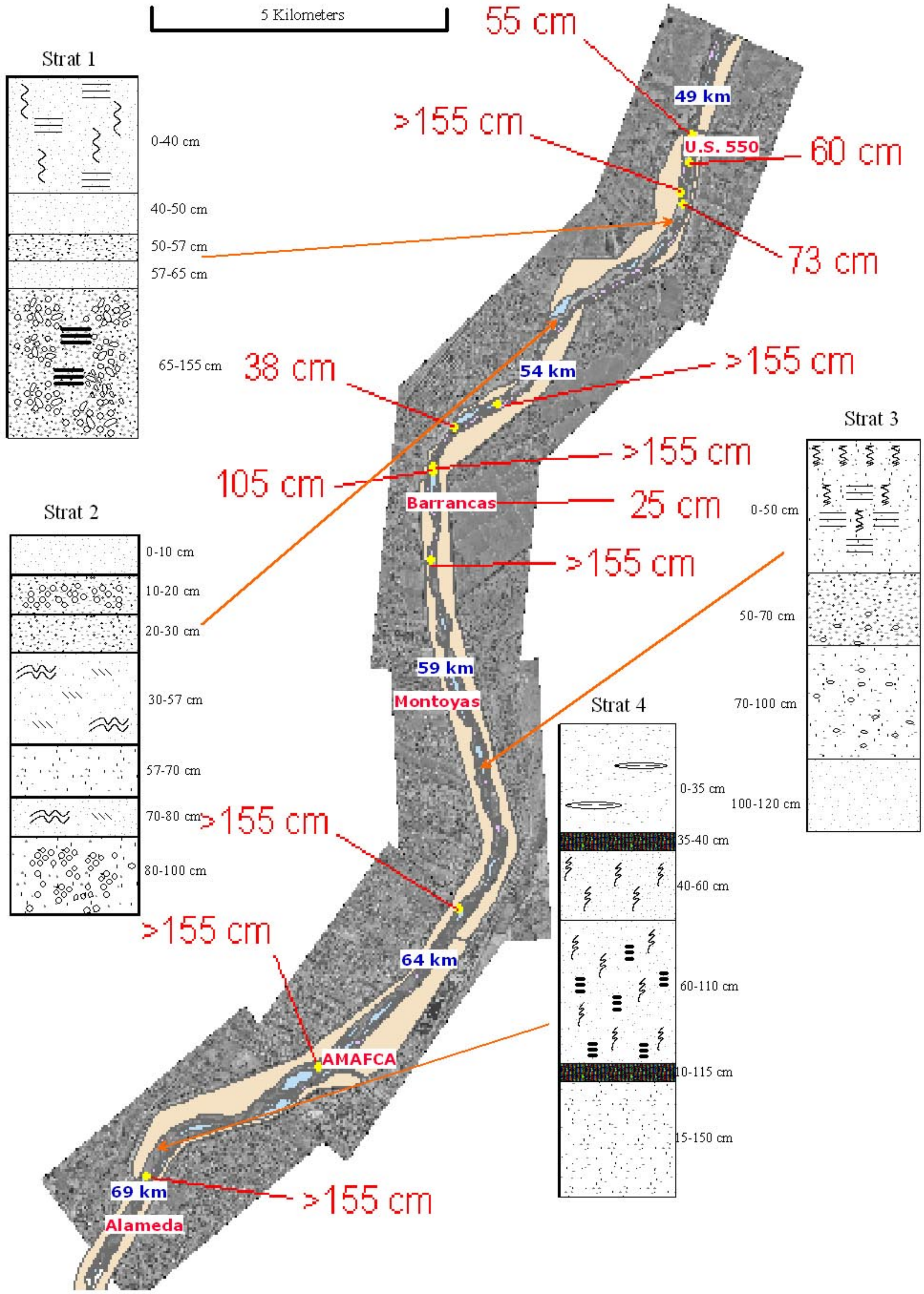


Figure 10. Reach wide sand depth measurements (cm) and locations, measured stratigraphic sections of bank and vegetated island sediments, and downstream distances from Cochiti Dam (km).

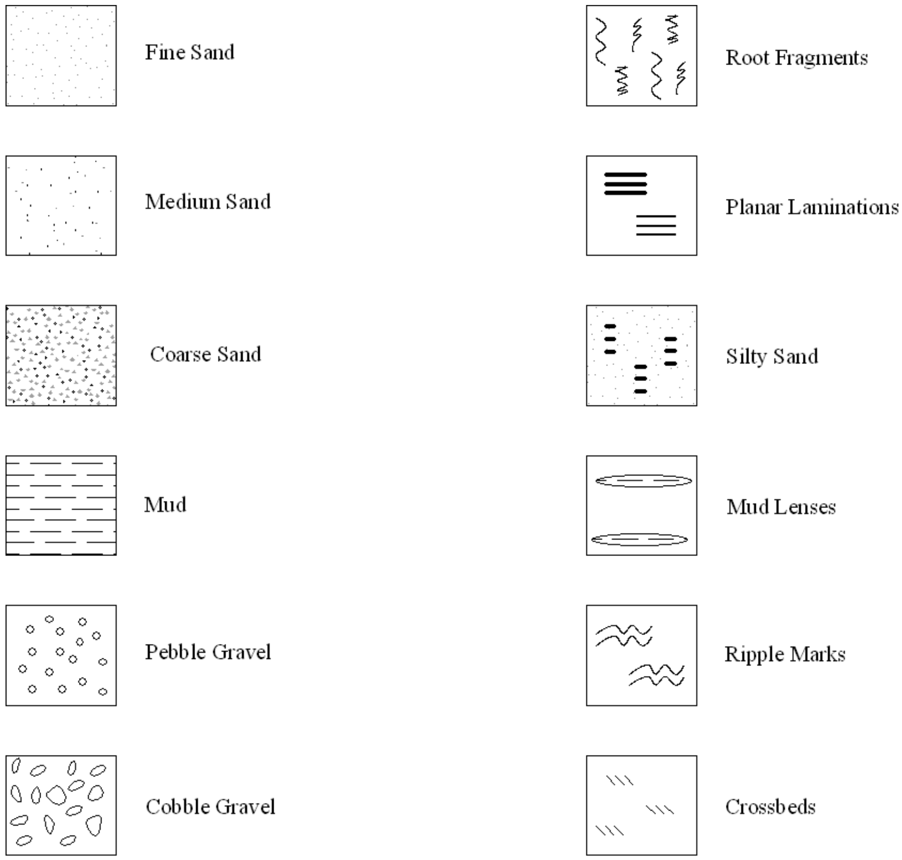


Figure 10 key.

About 10 to 50% of vegetated island sediments are composed of gravel-dominated units, with the most gravel-rich units found upstream of Arroyo de las Barrancas. In general throughout the study reach, pebble gravel was observed within each of the measured vegetated island sections, whereas the measured bank sediment section contained mainly sandy units.

The measured sections ranged in thickness between 100 cm and 155 cm (Fig. 10 and Appendix 1). Each of the measured sections had between four and seven individual units between 5 and 90 cm thick. The dominant grain sizes found within each of the units were medium to coarse-grained sands. Units with high percentages of gravel had medium to coarse-grained sand matrices. Although sedimentary structures were observed within a few units, they were not very prominent, and included laminar bedding, ripple marks, and minor small scale cross beds. Root fragments were also observed within three of the four measured sections. Based on field observations, I infer that the described section is reasonably representative of bank sediments found along the length of the study reach. Bank deposits are consistently composed of fine to coarse-grained sands with minor mud lenses along the entire study reach. Within sediments of vegetated islands, field observations indicate a dominance of medium to coarse sands and gravel in the upstream reach, with the percentage of gravel decreasing downstream.

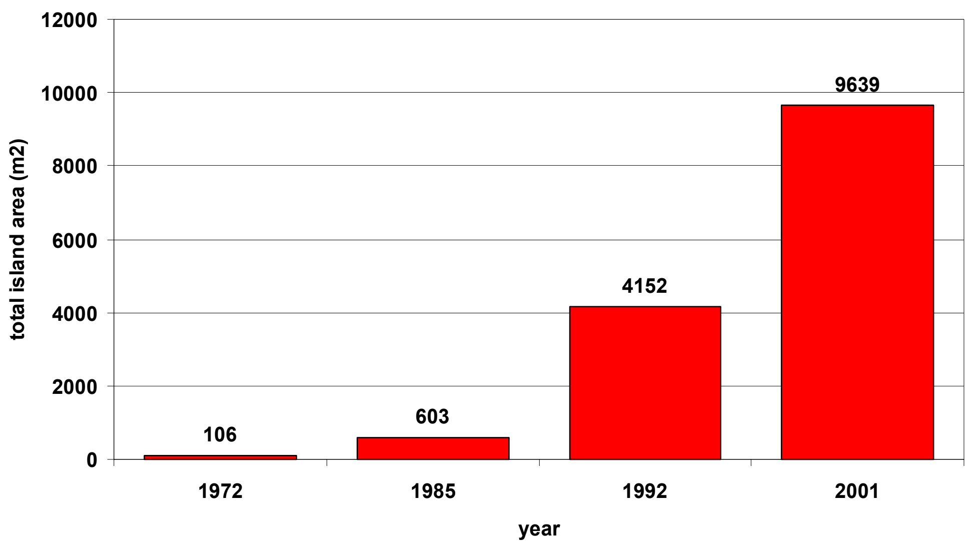


Figure 11. Changes in vegetated island areas since closure of Cochiti Dam. Island areas were calculated from shape files created in a GIS by Bureau of Reclamation personnel and University of New Mexico researcher.

*Vegetated Island Areas*

Total vegetated island area along the study reach has changed significantly since 1972 (Fig. 11). In 1972, two vegetated islands with a combined surface area of 106 $m^2$

were mapped within the study reach. In 1985, 12 years after the closure of Cochiti Dam, the number of vegetated islands had increased to 13. These islands had a combined surface area of 603 $m^2$. The most remarkable increase in total vegetated island surface area occurred between 1985 and 1992, a time of generally low to moderate peak flows. During that 7-year period, the number of vegetated islands increased to a total of 99, and the total surface area increased to 4152 $m^2$. Between 1992 and 2001 the total number reached 144 vegetated islands within the reach with a total surface area of 9639 $m^2$.

*Water Surface Profile*

The surveyed water surface profile indicates that the upper Rio Grande study reach between Bernalillo Bridge and the Arroyo de las Montoyas has an overall slope of 0.0008 at low flows. Below this arroyo mouth to near Alameda Bridge, overall slope increases slightly to 0.0009. The lower average slope of the upper reach is consistent with the observed greater incision of about 1 m in this area compared to the lower reach, assuming that the initial slope was similar.

There is also a slight local decrease in slope above the Arroyo de las Barrancas to about 0.0005, whereas adjacent to and directly downstream of the arroyo slope increases to 0.002 for about 50 m, and higher-velocity flow over the fan and downstream bar built by the arroyo is apparent. There is also a slope decrease above the Arroyo de las Montoyas, but a slope increase below is not apparent in the field, and because surveys across this area were done at different discharges, minor slope changes cannot be quantified.

*Channel Morphology*

As shown by repeat cross-sections and channel shape files provided by the Bureau of Reclamation, margins of the overall active channel in the study reach have not changed significantly at most locations since the late 1940s and early 1950s, when lines of jetty jacks were placed along the river corridor. There are a few eroded bank segments where flow in the incised thalweg is directed at high angle to the bank, such as a site of concern for potential levee breach on the eastern bank of the river channel approximately 3000 ft (914 m) downstream of the U.S. Hwy 550 Bridge. Flow over the fan at the Arroyo de las Barrancas is also directed strongly against the west bank directly downstream. Overall, however, bank erosion is clearly a very small contributor to the sand budget for the Rio Grande channel in this reach.

Between the Arroyo de las Barrancas and the Arroyo de las Montoyas there is an observable change in channel morphology. A single-threaded, locally island-braided channel with a deep, fast flowing thalweg undergoes a transition into a wider, multi-threaded, island and bar braided channel with shallow, slower-flowing multiple thalwegs (Fig. 12). Upstream, low discharges below 2000 $ft^3/s$ (57 $m^3/s$) create the dominant single threaded, island-braided planform. With increased discharges, various elevated channels become activated and create a multi-threaded, island-braided planform. Below Arroyo de las Montoyas the multi-threaded island- and bar-braided planform does not change as dramatically with discharge. At flows < 400 $ft^3/s$ (11 $m^3/s$), more sand bars become exposed and increase the number of channels present within the downstream section of the reach. Flows above 400 $ft^3/s$ combine some of these minor channels, but


Figure 12. Visible channel planform transition zone from a single-threaded, locally island-braided channel with a deep, fast flowing thalweg (upstream of Barrancas Arroyo) undergoes a transition into a wider, multi-threaded, island and bar-braided channel with shallow, slower-flowing multiple thalwegs (downstream of Montoyas Arroyo).

the number of vegetated islands and recently stabilized sand bars downstream of the Montoyas Arroyo keep an overall multi-threaded planform in place.

**Analysis and Interpretation**

Bed sediment variations within the study reach can be attributed to several factors. Field observations of the relative abundance of gravels within island sediments in contrast to the sandy bank sediments with very little gravel suggest that a significant amount of gravel has moved into the reach since closure of Cochiti dam. The island gravels may in large part represent coarser bed sediment moved into the study reach during post-dam channel incision upstream. It is also probable that at least some gravelly bed sediments within the reach are the result of winnowing of finer-grained sediment with channel incision and resulting development of a gravel lag. The scarcity of gravel in the main east and west banks along the entire reach along with the lack of shallow gravel deposits located by probing the bed, however, suggest that gravel is relatively rare in pre-dam floodplain deposits. Nonetheless, current gravel deposits may be the result of both processes.

Tributary inputs play an important role in bed sediment characteristics in the study reach, but the volume of this contribution is difficult to quantify, and can change dramatically with climate and storm events, land-use changes, and engineering modifications to channels. Leopold (1946) described a September 1941 thunderstorm that caused the Arroyo de las Calabacillas to flood at an estimated 10,000 $ft^3/s$ (285 $m^3/s$). Discharges for the Montoyas and Barrancas arroyos were estimated at 2000 to 4000 $ft^3/s$ (60-115 $m^3/s$). A large fan deposit at the mouth of the Calabacillas arroyo was estimated by Leopold (1946) to contain almost 150,000 $m^3$ of sediment, composed mostly of sand, although this flood also deposited some large boulders. A much greater volume of sand entered the Rio Grande channel and was carried downstream. This event, although uncommonly large, nonetheless illustrates the potential of the large arroyos draining the northern Llano de Albuquerque to contribute sandy sediment to the Rio Grande.

The transition zone between coarse and fine-grained material has progressed downstream since dam closure into its current position within the study reach. Lagasse, (1981, Fig. 14) illustrated a fairly abrupt grain size transition zone located at about river kilometer 35 in 1980, close to the mouth of the Jemez River. The present transition in bed sediment character is more gradual, but I estimate its position to be between river kilometer 51 and 55. The 16 km of downstream progression over the past 23 years translates into a rate of about 0.7 km/yr since 1980. It is unknown if the grain-size transition zone is currently moving downstream or at what rate. According to Williams and Wolman (1984), movement of this coarsening front will likely slow until a quasi-static transition zone develops, which may be controlled by tributary sediment inputs.

A notable change in median grain size variability occurs between the Barrancas and Montoyas arroyos. Above the Arroyo de las Barrancas pebble and cobble gravels are the predominant grain sizes within the active channel and thalweg. The majority of sand present within the overall active channel area above Arroyo de las Barrancas is being stored in high-flow channels along with additional pebble and cobble gravels. Based on field observations it is estimated that 95% of active channel bed sediment are pebble and cobble gravels. Stored sediment within high-flow channels consists of approximately 65% gravel and 35% sand within the upstream areas of the study reach. Downstream of the Arroyo de las Montoyas channel bed sediment composition is estimated at 95% sand and 5% pea and pebble gravels. Sediment stored within vegetated islands downstream of Arroyo de las Montoyas is estimated at approximately 85- 90% sand with the remaining sediment composed of pea and pebble gravels. Field observations in the upper study reach indicate that most high-flow channels are not activated until a discharge of 2500 $ft^3/s$ or more is reached, therefore sand stored in these locations cannot be moved at lower discharges.

The increase in total number of vegetated islands and island surface area can also be attributed to controlled discharges from Cochiti Dam. As flows are reduced and incision continues downstream, flow becomes confined to a smaller channel area, and more stable areas of sediment in storage become available for plant colonization by saltcedar, Russian olive, willows, and herbaceous plants. Plants stabilize large areas within the active channel zone (Milford et al., 2003) and promote further colonization along the margins of vegetated islands and at extreme low flows on top of emergent sand bars. When discharges remain low ($<1500$ $ft^3/s$ peak flows) throughout the year, more emergent sand bars are becoming stabilized which further decreases the availability of transportable sediment.

Two area of important sediment input into the study reach are located at the mouths of the Barrancas and Montoyas arroyos; likely the Calabacillas arroyo functions in this manner as well, but field data are not yet available. Grain size analysis at these locations indicates that grain sizes mainly between 128 mm and 0.125 mm are being introduced into the system, dominated by sand between 2 mm and 0.25 mm. Although granules commonly exist in bed sediment downstream to Alameda Bridge, field observations suggest that pebbles and cobbles (4- 256 mm) are not actively being transported downstream of the Arroyo de las Montoyas.

The build up of sediment at the arroyo mouths is observed within the water surface profile as the changing of the slope at both arroyo locations (Fig. 13). The slope changes at the Arroyo de las Barrancas and the Arroyo de las Montoyas indicates that coarse sediment input remains near the arroyo mouths and locally controls slope. At current discharges (< 1500 $ft^3/s$) the system is unable to remove the coarser fraction of introduced sediment, causing reduction of slope above the tributary fan. Downstream of the sediment sources water surface slope increases as water flows over the coarse sediment accumulation.

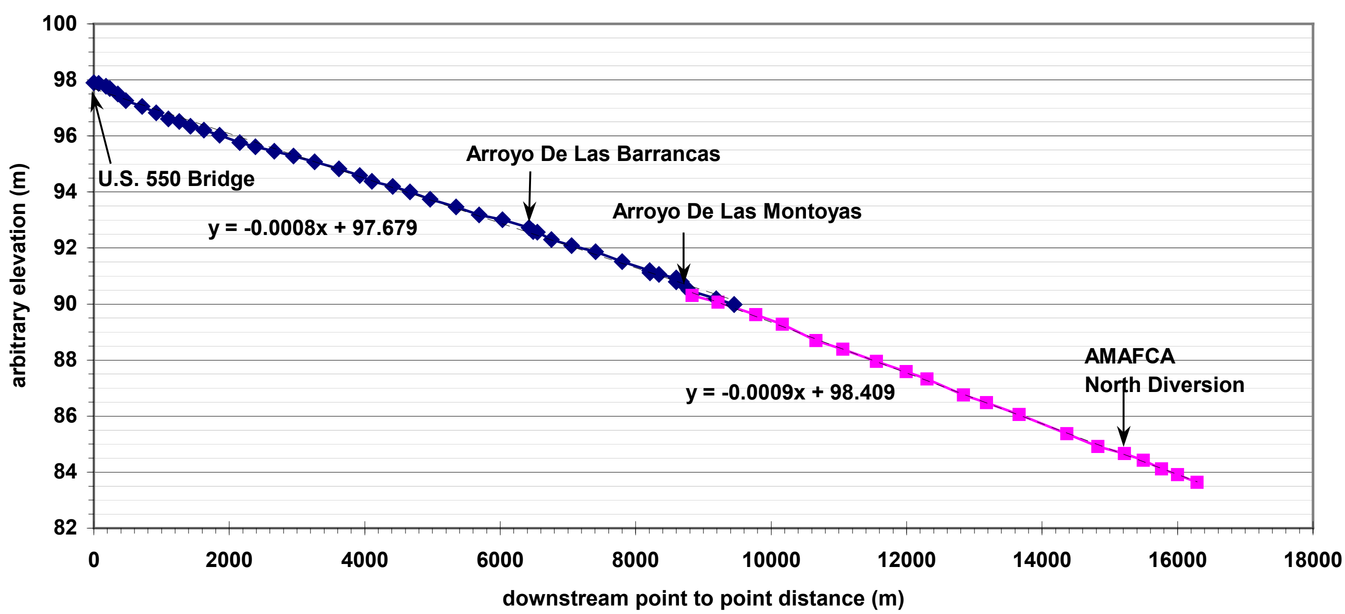


Figure 13. Long profile of study reach created from water surface survey data. Primary survey (blue line) locations were recorded using a differential GPS unit with sub-meter accuracy. Secondary survey (pink line) locations were recorded using a handheld Garmin GPS 12 unit with meter accuracy.

**Summary**

This project has shown that changes following closure of Cochiti Dam have affected the middle Rio Grande in a number of ways. Bed sediment along the length of the study reach has progressively become coarser, and the number of vegetated islands and associated stabilized surfaces has dramatically increased since the closure of Cochiti Dam. Sediment inputs from tributaries are important controls on grain size distributions and water surface slope changes within the study reach. The current rate of downstream progression of the coarse to fine grained transition zone is unknown. At higher discharges the grain size transition zone could possibly continue movement downstream. Continued channel incision will increase available surface area of bars and islands for plant colonization by saltcedar, willow, and other riparian species. This will further reduce the amount of stored sediment available for downstream transport at high discharges. Increased channel incision will also promote continued downstream formation of a dominant single-threaded, island braided river planform.

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## Appendix 1

| **Strat-1** | Vegetated island sediments located approximately 200 meters south of U.S. 550 bridge. The thickness of this section was 155 cm and contained five identifiable units. |
|---|---|
| **Depth** | **Description** |
| **0-40 cm** | fine grained sand, laterally continuous, thickness remains constant.<br>many roots present, laminar bedding visible, possible ripple x-beds |
| **40-50 cm** | fine-grained sand, with a high % of silt/clay. Layer is more resistant<br>to excavation |
| **50-57 cm** | thin sand layer, medium to coarse grained, no pebbles present<br>laterally continuous |
| **57-65 cm** | fine grained sand with a moderate amount of silt/clay.<br>forms cliff in cut. |
| **65-155 cm** | coarse sand to cobble gravels, mostly pebble gravels and very<br>coarse sand, laminar bedding visible and possible small scale x-beds. |
| | |
| **Strat-2** | Vegetated island sediments, located approximately 1200 meters south of U.S. 550 bridge, and had a total thickness of 100 cm with seven identifiable units |
| **Depth** | **Description** |
| **0-10 cm** | fine-sand, no visible sedimentary structures<br>this layer pinches out to left of measuring tape and thickens to the<br>right of the measuring tape. |
| **10-20 cm** | pebble gravel with minor coarse grained sand component.<br>laterally discontinuous |
| **20-30 cm** | coarse sand, layer thickness varies laterally.<br>forms sharp contact with layer below it. |
| **30-57 cm** | well sorted fine sand, laterally continuous<br>small ripple x-beds visible<br>thickness varies slightly laterally |
| **57-70 cm** | medium grained sand<br>laterally discontinuous, thickness varies laterally |
| **70-80 cm** | well sorted fine sand, laterally continuous<br>small ripple x-beds visible<br>thickness varies slightly laterally |
| **80-100 cm** | pebble gravels in a medium grained sand matrix<br>laterally continuous, although thickness varies |

| | |
|---|---|
| **Strat-3** | Vegetated island sediments located approximately 1000 meters south of the Arroyo de las Montoyas. This section was 120 cm thick with four identifiable units. |
| **Depth** | **Description** |
| **0-50 cm** | medium to fine grained sand, laterally continuous, planar laminations, small roots in upper 30 cm. |
| **50-70 cm** | medium to very coarse sand, some pea size gravel (<5%) gravel found at 69-70 cm depth. |
| **70-100 cm** | medium to coarse sands, some pebbles interspersed within unit (<7%). |
| **100-120 cm** | fine to medium sands, no pebbles, no sedimentary structures, laterally continuous. |

| | |
|---|---|
| **Strat-4** | Bank sediments located approximately 400 meters north of Alameda Bridge; its total thickness was 150 cm and had six identifiable units. |
| **Depth** | **Description** |
| **0-35 cm** | fine to medium grained sand, with minor mud lenses hardest layer of bank sediments, possibly due to precipitation Infiltrating into ground at site, fine grained, hard to determine composition of grains |
| **35-40 cm** | 5 cm thick dark brown mud layer |
| **40-60 cm** | very fine grained sand, ~ 20 cm thick, poorly sorted sub-angular to sub-rounded grains, reddish brown, many root fragments |
| **60-110 cm** | Sandy silt/clay. Rich in organics, many roots throughout layer, gradually coarsens upward into fine sand sand within the clay is fine to very fine grained becomes dominantly fine grained at 60 cm. |
| **110-115 cm** | 5 cm thick mud layer, this unit is hard and well compacted brown to black in color |
| **115-150 cm** | unconsolidated medium grained sand, poorly sorted angular to sub-rounded grains, sand body appears to have been oxidized |