

GEOMORPHIC RESPONSE OF THE RIO GRANDE TO DAM CONSTRUCTION

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ABSTRACT

Data in sufficient detail to support a qualitative assessment of the geomorphic response of the Rio Grande to the construction of main-stem dams are available for two reaches of the Rio Grande in New Mexico: below Elephant Butte Dam and below Cochiti Dam. Documentation of channel adjustments below Elephant Butte Dam during the period 1917-32 provides a set of interpretive keys to support a detailed analysis of the geomorphic response of the Rio Grande to the construction of Cochiti Dam in 1973. A comparison of cross-section, planform, and profile data is used to develop a time-sequenced picture of geomorphic change during the period 1970-80 in the 80-km (50-mi) reach of the Rio Grande below Cochiti. When correlated with the hydrologic record, hydraulic data, and the history of engineering activity in the reach this analysis provides a qualitative assessment, in terms of trends, of the response of a semiarid zone alluvial river to dam construction.

Regulation of discharge and alternation of sediment load following closure of Cochiti Dam required major adjustments in the alluvial system below the dam. In the upper reaches of the area studied, gravel armor and base-level control by the volume and size of sediment in arroyo and tributary deltas restricted change in the vertical dimension of the Rio Grande. Correlative adjustment in river planform was strongly influenced by channelization activities. In the lower reaches adjustment has been through significant shifts in longitudinal profile with relatively little change in planform. While degradation was limited by gravel armor and arroyo control in the upper reaches, it became the dominant process in the middle reaches of the area studied. In the lower reaches, an initial period of degradation was followed by aggradation as the heavy sediment load derived from upstream scour encountered a slightly reduced gradient and depletion of main channel flow by successive irrigation diversions. Available hydrologic data also permit the evaluation of the impact of an extended period of regulated low flow and a sustained period of high flow on system stability.

INTRODUCTION

This paper presents the results of a qualitative assessment of the geomorphic response of the Rio Grande to the construction of the main-stem dam at Cochiti, New Mexico. While the level of analysis is qualitative, not quantitative, the study was conducted in sufficient detail to support conclusions and recommendations in the following areas:

1. short and long range trends in river system stability;
2. the impact of arroyos (streams with steep gradients draining relatively small areas and contributing coarse sediment) and tributaries (streams with low gradients draining relatively large areas and contributing sand-size sediment) on river system stability;
3. the influence of permanent pools and the construction of sediment detention dams; and

4. consequences of the altered sediment regime for stability of jack fields below Cochiti.

Data for a qualitative analysis of the geomorphic response of the Rio Grande to the construction of dams on the main-stem are available for two reaches of the Rio Grande in New Mexico: below Elephant Butte Dam and below Cochiti Dam. Documentation of channel adjustments below Elephant Butte Dam during the period 1917-32 by the International Boundary and Water Commission has been used in this study to provide a set of interpretive keys for a more detailed analysis of the response of the Rio Grande to the construction of Cochiti Dam in 1973. A comparison of cross-section, planform, and profile data permits development of a time-sequenced picture of geomorphic change during the period 1970-80 in the 80-km (50-mi) reach of the Rio Grande between Cochiti and Isleta. Correlation of these geomorphic changes with the hydrologic record, hydraulic and sediment data, and the history of engineering activity in this reach provides a qualitative assessment of the response of the Rio Grande to dam construction. A secondary objective of the study was to support a more precise assessment of river response as well as the predictive capability that can be derived from physical-process computer modelling.

The study from which this paper was drawn (Lagasse, 1980b) provides a detailed analysis of the Cochiti to Isleta reach in the post-dam period. Additional topics such as the consequences of adopting dredging as a maintenance alternative on the Rio Grande and the potential impact of neotectonic activity along the Rio Grande rift on long-term river system stability are addressed in the original study; whereas, this paper presents a greatly abbreviated version of that study.

To provide the necessary setting for the analysis which follows, the physiographic characteristics of the middle Rio Grande, the sequence of pre-dam engineering development in the Cochiti to Isleta reach, and response to development in this reach are reviewed briefly. A survey of documentation on degradation (general lowering of the channel bed) below dams on other river systems and a brief discussion of the armoring process are also essential background material. The general trends in geomorphic response of the Rio Grande to the construction of Cochiti Dam are then analyzed, with a discussion of response in each of the three dimensions: profile, planform, and cross section. This analysis is followed by a synthesis of response, with particular emphasis on the impact of arroyos, tributaries, and sediment detention dams on river system stability in the post-dam period. The conclusions address engineering areas of concern for agencies with operational responsibilities for the Rio Grande system.

THE RIVER SYSTEM

The general group of basins, canyons, and constrictions that comprises the area known as Middle Rio Grande Valley begins at the southern end of White Rock Canyon and terminates at the San Marcial constriction, some 230 km (143 mi) downstream (fig. 1).

RIO GRANDE LOCATION MAP

20 0 20 40
SCALE OF MILES

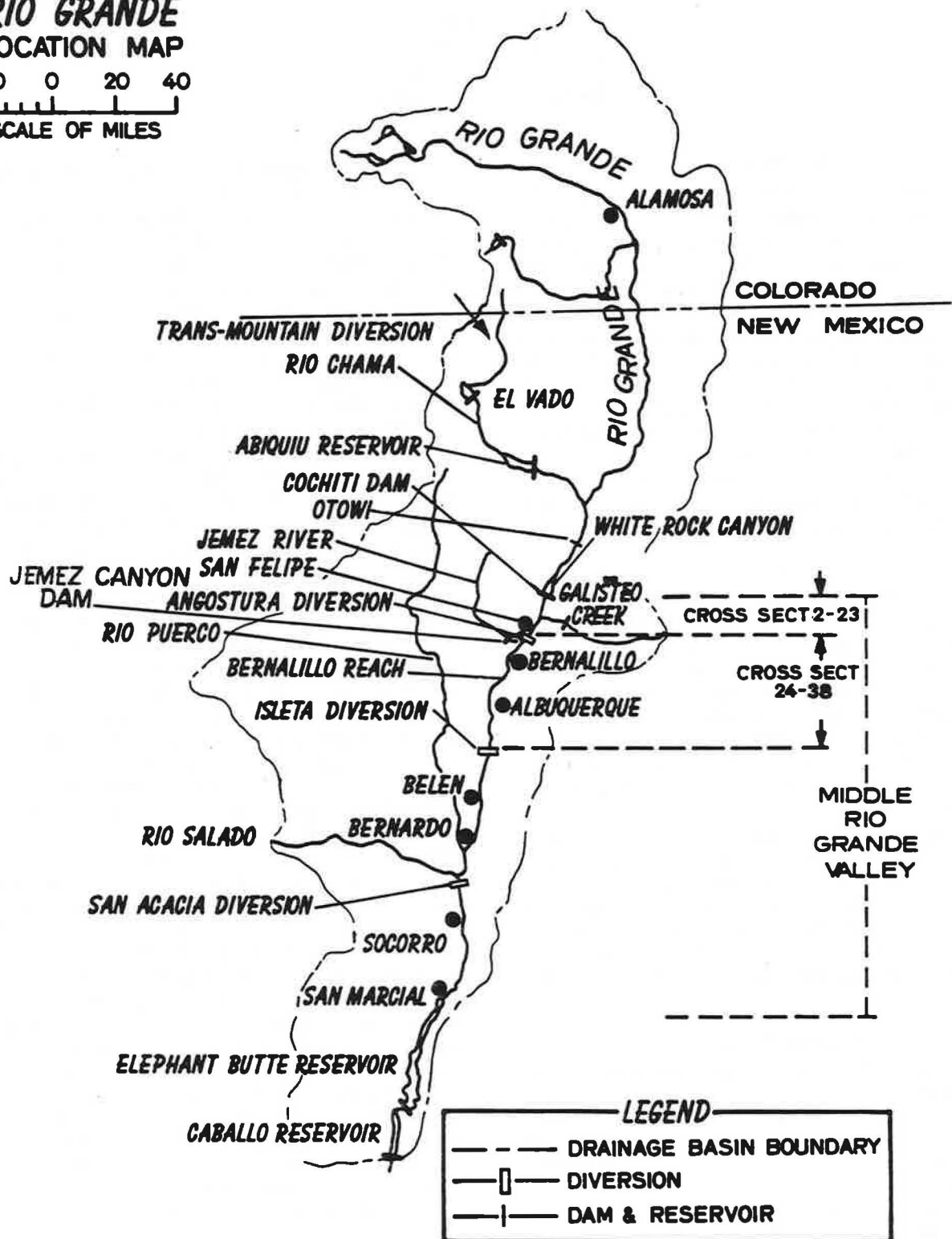


Figure 1. Middle Rio Grande Valley showing Cochiti to Isleta study area.

Several hundred meters of lower Cenozoic continental sediments underlie upper Cenozoic sediments in a large portion of several of the basins. The Middle Rio Grande Valley is broken by short canyons or narrows at San Felipe, Isleta, and San Acacia, which, in turn, define the subvalleys or basins of Santo Domingo, Albuquerque, Belen, and Socorro. Because the diversion dams at Angostura (north of the Jemez River confluence) and Isleta (midway between Albuquerque and Belen) (fig. 1) act as "geologic" controls of river base level and may limit upstream and downstream river response, this study does not consider response of the Rio Grande below the Isleta Diversion.

The channel of the middle Rio Grande consists of a shifting sand substratum with low, poorly defined banks. The flood plain contains a mixture of cottonwood, willow, Russian olive, and saltcedar, which together form a dense growth of riparian woodland (known as bosque) interspersed with pasture and cultivated land. The configuration of the river may be described as one of low sinuosity with some straight reaches. Formation of sediment bars in the channel during low-flow periods and, in particular, during the recession of flood flows, together with rapid growth of vegetation, generally determine the channel configuration within the levees. The slope of the river drops about 0.95 m/km (5 ft/mi) from Cochiti to a point just below Albuquerque, and about 0.76 m/km (4 ft/mi) from a point just below Albuquerque to the confluence of the Rio Puerco. Within the unstabilized floodway, the channel has virtually no banks, and the bed of the river is at or above the level of areas outside the levees due to sediment deposition between the levees.

In a detailed study of sediment transport in the Rio Grande, Nordin and Beverage (1965) provide an excellent picture of the hydraulic characteristics of the Rio Grande prior to the construction of Cochiti Dam. Between Cochiti and San Felipe the channel was braided between many bars and islands composed of coarse gravel and cobbles. The bed was composed of sand at low discharges and of sand and gravel at higher flows. Downstream from the confluence of the Jemez River the Rio Grande was a sand-bed stream. Studies by the U.S. Bureau of Reclamation (presently known as the U.S. Water and Power Resources Service) for the design of the middle Rio Grande channelization indicated that for the pre-dam river the dominant, or channel-forming, discharge, was in the range of $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) (Schembera, 1963).

The surface flows of the middle Rio Grande are of two general types. One type occurs from April through June as a result of snow melt which may be augmented by general precipitation. These spring flows are characterized by gradual rises to moderate discharge rates, large runoff volumes, and approximately two-month flow durations with shorter duration peak flows included. The other type is a summer or flash flow that may occur from May through October. Summer flows are characterized by sharp high peaks that recede quickly and generally contain smaller runoff volumes. In the Middle Rio Grande Valley, flows above $142 \text{ m}^3/\text{s}$ ($5,000 \text{ ft}^3/\text{s}$) are considered flood flows.

There are several major tributaries in the reach below Cochiti Dam. Galisteo Creek, which enters the Rio Grande from the east about 13 km (8 mi) below Cochiti, is a large contributor of sediment and has a history of flash-flood events. Arroyo Tonque also enters from the east approximately 11 km (7 mi) below Galisteo Creek, just above San Felipe. This arroyo runs infrequently but does contribute sediment to the Rio Grande. Culbertson and Dawdy (1964) noted that in the confined San Felipe reach, velocities are relatively high, and bed material in the sand range brought in by Galisteo Creek and Arroyo Tonque apparently is

moved through the reach, as there is little evidence of general aggradation. The Jemez River enters the Rio Grande from the west about 13 km (8 mi) below San Felipe. Prior to completion of the Jemez Canyon Dam the Jemez River brought large sediment loads to the Rio Grande. The consequences of changing operational procedures at Jemez Canyon Dam and the potential impact on the Rio Grande of a permanent pool in Jemez Reservoir are discussed in this paper.

In a study of sources of modern sands in the Middle Rio Grande Valley, Rittenhouse (1944) found that of the channel and floodway deposits between Albuquerque and Bernardo, 21 to 39 percent of these deposits came from the Jemez River, 2 to 6 percent from Galisteo Creek, 0.6 to 2 percent from the Santa Fe River, 11 to 37 percent from the Rio Grande above Cochiti, and the rest from smaller tributaries for which separate evaluations were not made. An average of $2.2 \times 10^6 \text{ m}^3$ ($1,800 \text{ acre-ft}$) of sediment reaches Cochiti reservoir each year. Over 40 percent of the annual inflow of sediment to Cochiti comes from the Rio Chama basin below Abiquiu Dam. With Jemez Canyon, Galisteo, and Cochiti dams operating in concert, it is estimated that about 80 percent of the sediment inflow to the Rio Grande above Albuquerque is controlled (U.S. Army Engineer District, Albuquerque, 1978).

PRE-DAM DEVELOPMENT AND RIVER RESPONSE

Concern over the decrease in irrigated acreage along the Rio Grande resulted in the formation of the Middle Rio Grande Conservancy District in 1925. From 1925 to 1935 the Conservancy District constructed, operated, and maintained four major diversion dams (Cochiti, Angostura, Isleta, and San Acacia), two canal headings, and many kilometers of drainage canal, river levees, and main irrigation canals. The basic flood control structures consisted of levees which were placed parallel to the river. The average width of the floodway within the levees was about 457 m (1,500 ft), and the average height of the levees was about 2.4 m (8 ft).

As a result of continued problems in the Middle Valley, the Corps of Engineers and the Bureau of Reclamation jointly prepared the "Rio Grande Comprehensive Plan." The Corps of Engineers' portion of the Comprehensive Plan provided the Jemez Canyon Dam in 1953, Abiquiu Dam and Reservoir in 1963 on the Rio Chama, Galisteo Dam in 1970, and Cochiti Dam and Reservoir on the main stem in 1973. The system consisting of Abiquiu, Jemez Canyon, Galisteo, and Cochiti dams, and the levees along the Rio Grande provides flood control for the Middle Rio Grande Valley.

Cochiti Dam (closed in November 1973) is a rolled earthfill embankment with a crest length of over 8 km (5 mi) and a crest height of 76.20 m (250 ft) above the Rio Grande stream bed (fig. 2). Reservoir capacity is $740 \times 10^6 \text{ m}^3$ ($6.0 \times 10^5 \text{ acre-ft}$), and at the top of the flood-control pool the lake has a surface area of $38 \times 10^6 \text{ m}^2$ (9,360 acres) and extends about 32 km (20 mi) upstream. The outlet works include a gated intake structure, a three-barrel conduit, and a terminal stilling-basin structure. Maximum discharge capacity through the conduits at maximum pool stage is $425 \text{ m}^3/\text{s}$ ($1.5 \times 10^4 \text{ ft}^3/\text{s}$). A spillway is located on the left abutment at the southern end of the embankment on the Santa Fe River. Above the spillway the Santa Fe River is diverted through a conveyance channel to Cañada de Cochiti and Cochiti Reservoir.

Cochiti Dam permits control of the main stem of the Rio Grande above the Middle Valley, a control not previously available. As originally planned, this dam was intended for flood control and sediment control only. Multipurpose development objectives included arresting damaging flood flows, retaining sediment, and inducing degradation. Concern for recreation led to a modification



Figure 2. Aerial view of Cochiti Dam.

of the authorization, and a permanent pool of $62 \times 10^6 \text{ m}^3$ (5.0×10^4 acre-ft) has been formed with water from the San Juan-Chama Project.

The Bureau of Reclamation's part of the Rio Grande Comprehensive Plan included channel rectification work along the Middle Rio Grande. Above the Angostura Diversion levees are discontinuous and the width of the floodway varies erratically from about 153 to 763 m (500 to 2,500 ft). In order to confine the channel, permeable steel jetties in combination with natural vegetation and topographic features were employed. Between Cochiti and Bernardo the floodway is generally confined by levees and averages 458 m (1,500 ft) wide through intensively developed rural and urban areas. Both the Bureau of Reclamation and the Corps of Engineers installed jetties in this reach, varying the density and widths as guided by hydraulic model studies. Design channel widths decrease in a downstream direction from 274 m (900 ft) in the Cochiti reach to 168 m (550 ft) at Bernardo. Operated in conjunction with upstream reservoirs, this channel work was intended to reverse the trend of aggradation and to allow the channel to degrade back to essentially a 1936 condition.

Before construction of Cochiti Dam and upstream tributary dams, the floodway of the Rio Grande was aggrading at rates as high as 0.6 m (2 ft) every 50 years near Albuquerque and as much as 5 m (16 ft) in 50 years near San Marcial. The ultimate result of aggradation is an increase in the height of the riverbed or floodway above the adjacent flood plain. By 1960, the river channel near Albuquerque was 1.8 to 2.4 m (6 to 8 ft) above the elevation of lands outside the levees. Woodson and Martin (1963) provide an excellent summary of the effects of the Rio Grande Comprehensive Plan on river regime through the Middle Valley of the Rio Grande. As of 1963 it was apparent that:

The Rio Grande within the Middle Valley is still an aggrading stream, and construction of the floodway has not halted ag-

gradation. Aggradation has occurred in amounts varying from practically zero in the Cochiti Division at the upstream end of the valley to a maximum of about 0.04 of a foot per year in the Albuquerque Division.

They also noted significant increases in sediment inflow in the Angostura to Bernalillo reach and attributed it to the Jemez River which enters the Rio Grande between those two locations. In regard to anticipated response to reservoirs (Abiquiu, Jemez, Cochiti, and Galisteo), Woodson and Martin concluded in 1963 that the sediment inflow at Bernalillo would be reduced by reservoirs about 75 percent after about 20 years and that the existing trend of aggradation would be reversed. Indications were that degradation would begin at Cochiti and extend downstream at least to the Rio Puerco. Progressive coarsening of the stream bed was expected to inhibit degradation, and it appeared unlikely that the channel would degrade more than about 0.9 m (3 ft) in the Bernalillo to Albuquerque reach.

DEGRADATION AND CHANNEL ARMORING

The principal objective of the present study was to assess the response of the Rio Grande to dam construction, and that response involves a consideration of both degradation and the channel-armoring process. The literature on channel degradation below dams and channel armoring is too voluminous to be reviewed completely. For a detailed review and a listing of the significant publications concerning these processes, reference to Lagasse (1980b) is suggested. This section provides a brief summary of the current level of understanding and ability to predict the end result of these processes.

Prior to 1950 the analysis of degradation below dams was largely empirical, based on field observations (Gilbert, 1917; Lane, 1934). Stanley's (1948) analysis of the effect of dams on channel regimen

is representative and introduced the response of the Colorado River to Hoover Dam as a basis for analysis. The approach to the analysis of degradation below dams was broadened after 1950. Newton (1951) conducted an experimental investigation of bed degradation in open channels with particular reference to the problem on alluvial rivers below large dams. His laboratory investigation was an attempt to simulate the process in nature, but under controlled conditions, and illustrate the general "process and pattern" of degradation. This laboratory investigation introduced the concept of the degradational wedge, deepest at the dam or barrier and tailing out in a downstream direction, with stream-bed elevations and slope decreasing asymptotically with time.

Tinney (1962), and Komura and Simons (1967) developed analytical techniques for predicting degradation as limited by the development of an armor layer. As the latter study was the most detailed and was designed to be applied to the field condition, it can be considered representative of the state-of-the-art in predicting riverbed degradation below dams at that time. Komura and Simons recognized that the riverbed below a dam degrades due to the arrest of sediment transport by the reservoir. In the process of degradation finer fractions of the bed material are removed from the bed surface by hydraulic sorting and are transported downstream. As a result, the riverbed in the upstream reaches is armored with coarser bed material, an equilibrium state is established, and the process of degradation is terminated. A mathematical equation was developed to predict the final equilibrium profile of the riverbed under the described conditions. In illustrating the application of the procedure with numerical examples, several assumptions were required:

1. sediment transport is completely arrested by the dam;
2. river banks are not erodible;
3. no seasonal variations in discharge or water temperature occur;
4. sediment injections by tributaries do not occur; and
5. meandering of the river and growth of vegetation do not occur.

The end result of this approach is the mathematical determination of the slope of the degradational wedge between the dam and some downstream control or reference section, for either a transient phase or final equilibrium. Komura and Simons (1967) recognized the importance of sediment inflow from tributaries both in the assumptions listed above and in the recommendations for future studies at the conclusion of their paper.

Several studies have analyzed the process of armor layer formation in detail (Livesey, 1963; Hallmark and Smith, 1965). As described by Livesey, the armoring process begins as the nonmoving coarser particles segregate from the finer material in transport. The coarser particles are gradually worked down into the bed where they accumulate in a sublayer. Fine bed material is leached up through this coarse sublayer to augment the material in transport. As movement continues and degradation progresses, an increasing number of nonmoving particles accumulate in the sublayer. This accumulation interferes with the leaching of fine material so that the rate of transport over the sublayer is not maintained at its former intensity. Eventually, enough coarse particles accumulate to shield, or "armor," the entire bed surface. When fines can no longer be leached from the underlying bed, degradation is arrested.

Examination of typical armor layers reveals two important characteristics:

1. less than a single complete covering layer of larger gravel

particles seems to suffice for a total armoring effect for a particular discharge; and

2. a natural "filter" apparently develops between the larger surface particles and the subsurface material to prevent leaching of the underlying fines.

An armor layer sufficient to protect the bed against moderate discharges can be disrupted during high flow but may be restored as flows diminish. It is evident that an armor layer will tend to accumulate in areas of natural scour in the river, such as on the upstream end of islands and bars. Investigations and observations support the conclusion that less than a complete covering of a relatively thin armor layer plays a key role in stabilizing the bed, bars, and islands of alluvial rivers. Schumm (1977) notes that "an insignificant fraction of the alluvium (coarsest 1 percent) may significantly control the behavior and morphology of the channel."

Field observation, experimental investigation, and analytical study of degradation and armoring have produced a wealth of documentation on degradation and the armoring process. The temporal and spatial characteristics of degradation below dams on numerous river systems have been observed and reported, providing a basis for developing empirical techniques for predicting alluvial-channel response below dams. Armor layer characteristics have been observed, and the process of armor layer development has been analyzed in detail. Yet, the problem is so complex that analytical techniques provide the means of predicting only some variation on the "classic" degradational wedge, deepest at the dam and tailing out in a downstream direction to a geologic or structural control. It is recognized that bank erosion, discharge variability, meandering, and sediment inflow from tributaries affect channel response below dams, but analytical techniques have not addressed response in the complex environment implied by these variables.

Recent work by Simons and Li (1978) indicates that physical-process computer modelling provides a reliable methodology for analyzing the impacts and developing solutions to complex problems of aggradation, degradation, and river response to engineering activity. The approach can be used to estimate deposition, erosion, and armoring in systems subjected to different hydrologic inputs and operational alternatives, and permits simultaneous consideration of other important factors such as storage reservoirs and channel stabilization. The computational procedure involves the use of a sediment transport equation, the sediment continuity equation, equations of channel geometry, and routing sediment by size fractions to account for armoring effects. These provide a mathematical model based on the physical principles governing water and sediment transport as well as degradation and armoring processes, that is, a physical-process mathematical model.

ANALYSIS OF RESPONSE

Methods of Analysis

Depending on the data and resources available for analysis, the problem of assessing river system response to engineering activity and hydraulic structures can be approached in three phases:

1. a qualitative analysis based on general geomorphic parameters;
2. a quantitative analysis based on specific geomorphic and hydraulic data; and
3. a mathematical model of watershed and channel processes in the reach or system of concern.

As listed, each phase requires an increasing commitment of resources, but each phase individually yields meaningful results.

These range from a purely qualitative assessment of trends to the numerical results and predictive capability of physical-process computer modelling. When applied sequentially this multiphase approach constitutes a powerful methodology for the evaluation of short- and long-range response of river systems to development. This section outlines the qualitative geomorphic analysis techniques developed to assess the response of a semiarid zone alluvial river to the construction of a main-stem dam. An illustration of the approach used to analyze planform, profile, cross-section, and sediment data is provided.

While a qualitative analysis itself will yield meaningful results, refinement of conclusions resulting from such an analysis and a more precise assessment of trends, as well as a predictive capacity, can be derived from quantitative analysis and mathematical modelling. Calibration of a physical-process computer model involves evaluation and modification of supplementary relations to the basic physical-process equations so that the model will reproduce the historical response of the modelled river system. Establishing the geomorphic trends which constitute this historical response by a qualitative analysis, then, provides an essential basis for model calibration and verification.

Interpretive Keys (Elephant Butte Dam)

Documentation of channel adjustments below Elephant Butte Dam during the period 1917-1932 was used to provide a set of interpretive keys for the more detailed analysis of the response of the Rio Grande to the construction of Cochiti Dam in 1973. That is, the formative stages of the Cochiti analysis were guided, and to a certain extent structured, by documented response in the reach below Elephant Butte (International Boundary and Water Commission [U.S. and Mexico], 1932; Fiock, 1931).

After the closure of Elephant Butte Dam in 1916 there were two primary sources of sediment for flows through the Rio Grande below the dam: river bed scour by the clear water released from the reservoir and tributary inflow. The material derived from the steep-sloped, ephemeral tributary channels (arroyos) ranged from sand and gravel to boulder size and was deposited in a fan or delta at the tributary outlet, where it was available for transport by main-channel flows. Scour of the river channel itself by clear water released from storage was considered to be the principal sediment source, particularly in the sand size range. It was expected that this would remain the primary source of sands so long as the readjustment of the river channel to the changed conditions of clear, regulated flows continued.

Where an arroyo or tributary deposited directly into the main channel in a valley section below Elephant Butte Dam, the coarser material, which was beyond the competence of regulated main-channel flows, forced the Rio Grande channel away from the tributary outlet through erosion of the opposite bank. Where the tributary channel entered the Rio Grande in a canyon section the deposits of heavier debris created obstructions in the river channel causing backwater above and rapids over the tributary delta. Regulated high flows were not of sufficient magnitude or duration to transport this coarser material downstream. Thus, arroyo and tributary deposits created base-level controls along the main-stream and strongly influenced the processes of degradation and aggradation.

An analysis of the effects of clear-water scour along the Rio Grande below Elephant Butte Dam using successive cross sections indicated that there was a lowering of the river channel through the upper portion of the project of approximately 0.6 m (2 ft) during the first 15 years of reservoir operation. In the narrow Palomas

Valley below Elephant Butte Dam, numerous steep arroyos enter the river directly, carrying large quantities of coarse material. The sand bed of the Rio Grande in this reach developed a gravel lining as the finer material was transported downstream. General degradation extended through the Mesilla Dam reach (161 km [100 mi] below Elephant Butte Dam) but was more pronounced above Mesilla Dam than below.

Surveys and Flow Data

The U.S. Geological Survey (USGS) Water Resources Investigation by Dewey and others (1979) was a primary data source for analysis of the Cochiti to Isleta reach. This document contains a brief description of the study reach and survey methods as well as tables of sediment-transport data, hydrologic data, cross-section data, and computer-generated cross-sectional plots. The report (Dewey and others, 1979) documents changes in cross sections with time and space and changes in size distribution of sediments (before and after closure of the dam) for a series of surveys from 1970 to 1975 at 37 cross sections established along a 97-km (60-mi) study reach from Cochiti Dam to the Isleta Diversion.

The cross sections were surveyed at six-month (or shorter) intervals between May 1970 and November 1975. Subsequent to the completion of the USGS hydrologic data report the Corps of Engineers Albuquerque District funded four resurveys of these cross sections by USGS personnel. Field notes and computer-tabulated data are available for the surveys of April/May 1979, July 1979, and January 1980 and have been incorporated into this study to extend the USGS hydrologic-data base. The fourth resurvey completed in September 1980 was not available for this study, but the field notes from the survey have been reviewed.

Figure 3 shows the ten-year discharge hydrograph developed from published USGS Water-Supply Papers for the January 1971 to January 1979 period. The 1980 discharge values are from unpublished Corps of Engineers and USGS data. The maximum, mean, and minimum monthly discharges at the "below Cochiti Dam" gaging station are shown. The survey periods for the six surveys selected for detailed analysis in this report are also plotted. Of the many surveys available in the USGS hydrologic-data report (Dewey and others, 1979) three were selected as representative of the pre-dam and immediate post-dam period. The survey of May 1971 provides the earliest complete record of pre-dam conditions for all 37 cross sections. Comparison between data from this early survey and conditions during the June 1973 survey, which preceded closure of Cochiti Dam in November 1973, represents trends in the "natural" (unregulated) processes of the reach during the pre-dam period. The survey of November 1975 is the latest included in the USGS report and provides a view of Rio Grande response to Cochiti Dam under regulated-flow conditions during the two years following closure of Cochiti Dam. The supplemental surveys of April and July 1979 bracket a period of the highest peak, mean, and minimum monthly flows since the closure of Cochiti Dam. The April-July 1979 period also provided the longest record of sustained high flows in the last 10 years, with flows in excess of 142 m³/s (5,000 ft³/s) most of the period.

Planform Analysis

The pre-dam planform configuration of the Middle Rio Grande has been described as one of low sinuosity with some straight reaches and a "braided" channel. Examination of maps and aerial photographs reveals that the full range of channel patterns exists in the Cochiti to Isleta reach, from straight, to meandering, to braided. A time-sequenced picture of river position and river form

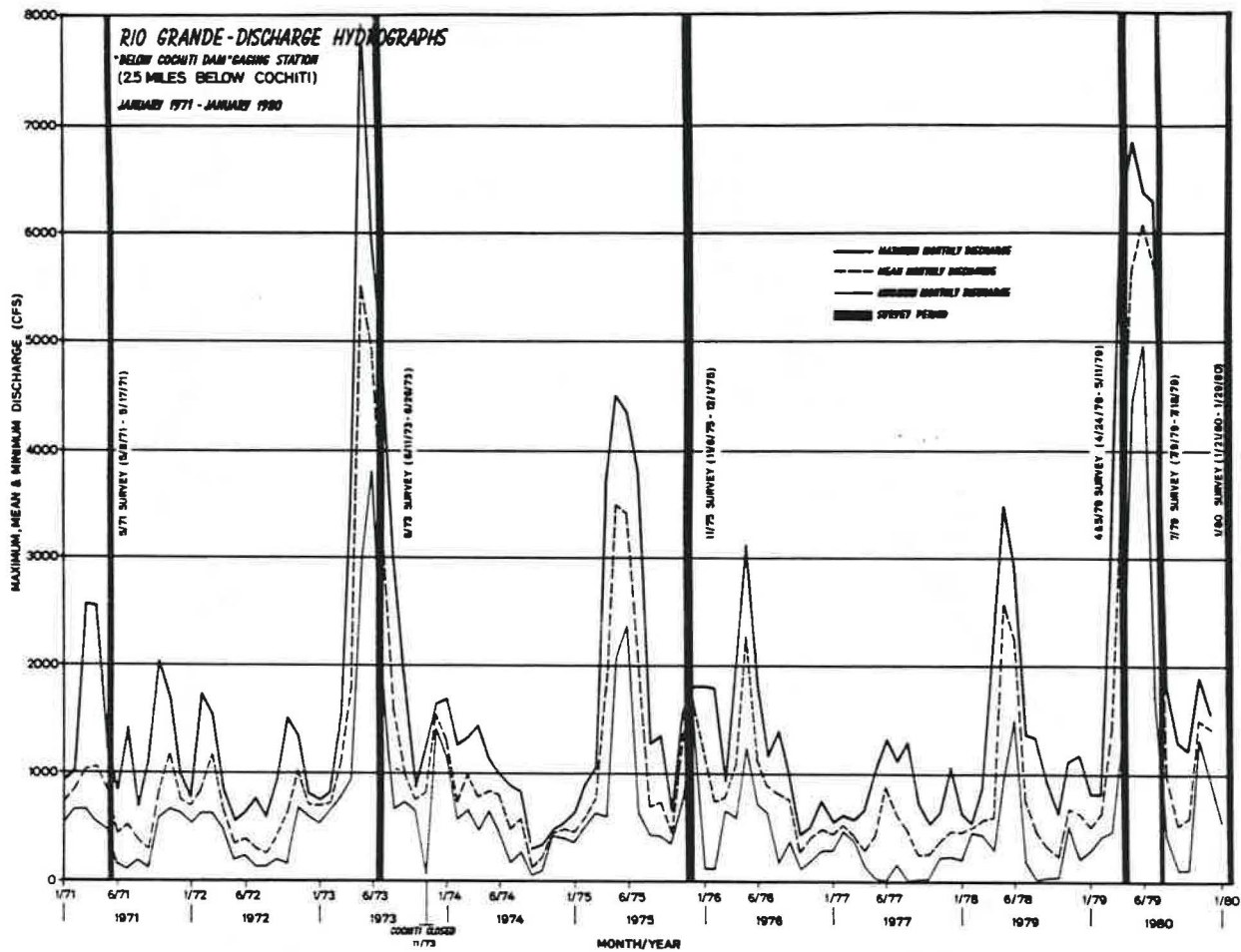


Figure 3. Discharge hydrographs at "Below Cochiti Dam" gaging station (1971-1980). Hydrographic survey periods also shown.

obtained by cross plotting the 1978 revised USGS topographic quadrangle sheets on the baseline provided by the 1953 quadrangle sheets indicates significant lateral change in the upper reach between Cochiti and San Felipe (fig. 4). Between San Felipe and Angostura there was only limited out-of-channel change in the pre-dam to post-dam period. Below Angostura all variations in plan have taken place within a well-defined floodway channel with banklines established and controlled by multiple lines of jackfields, heavy bosque vegetation, and levees. At the lower end of the study reach (fig. 5) a decrease in sinuosity is evident, with a shifting in the position of many alluvial islands and development of an almost braided channel planform.

Based on this comparison, then, the Rio Grande between Cochiti and San Felipe has experienced significant change in position and form in the pre-dam to post-dam time frame. Several braided reaches between cross sections 3 and 7 (fig. 6) have evolved to a reasonably well-defined main channel and chute channel configuration with the loss of numerous alluvial islands. Shifts in the position of the main channel by more than 305 m (1,000 ft) have occurred (for example, between cross sections 7 and 8 above Galisteo Creek [fig. 4]). Similar evolution in position and character can be found between Santo Domingo and San Felipe, but below this reach planform change is restricted to shape, position, and number of island within a well-defined channel.

Frequent reconnaissance by USGS personnel during the post-dam period indicates that human activity has been responsible for

some of the channel change in the reach between Cochiti and San Felipe. Windrows of sand and gravel, remnants of bulldozer activity in the channel during low flows, are evident both on the aerial photographs and in the field. Spilling of high-stage flows into old channels bypassed by human efforts may have contributed to braiding in the reach. Channel migration in planform in excess of about 61 m (200 ft) should generally be considered human-induced and not a natural response of the system. For example, the effects of channelization are readily apparent at cross section 9 below the Santo Domingo Bridge in Figure 4 where the left (east) channel around a large island has been shifted west approximately 183 m (600 ft).

Longitudinal Profile Analysis

Time-sequenced thalweg profiles for the Cochiti to Isleta reach provide an indication of trends in aggradation and degradation during the pre-dam to post-dam period. Figure 6 shows, for the entire reach, an overview comparison between the early pre-dam survey (May 1971) and conditions under the sustained high flow of April-July 1979. Figures 7 through 10 illustrate a division of the upper half of the study reach into subreaches using 15-m (50-ft) increments of elevation and show all six of the survey periods used in the study.

At the scale of the overview profile plot (fig. 6) little, if any, change is apparent from Cochiti Dam to cross section 9 just below Galisteo Creek, approximately 13 river km (8 river mi) down-

RIO GRANDE PLANFORM Sections 8-11

1000 0 1000 FT
SCALE: 1:24,000

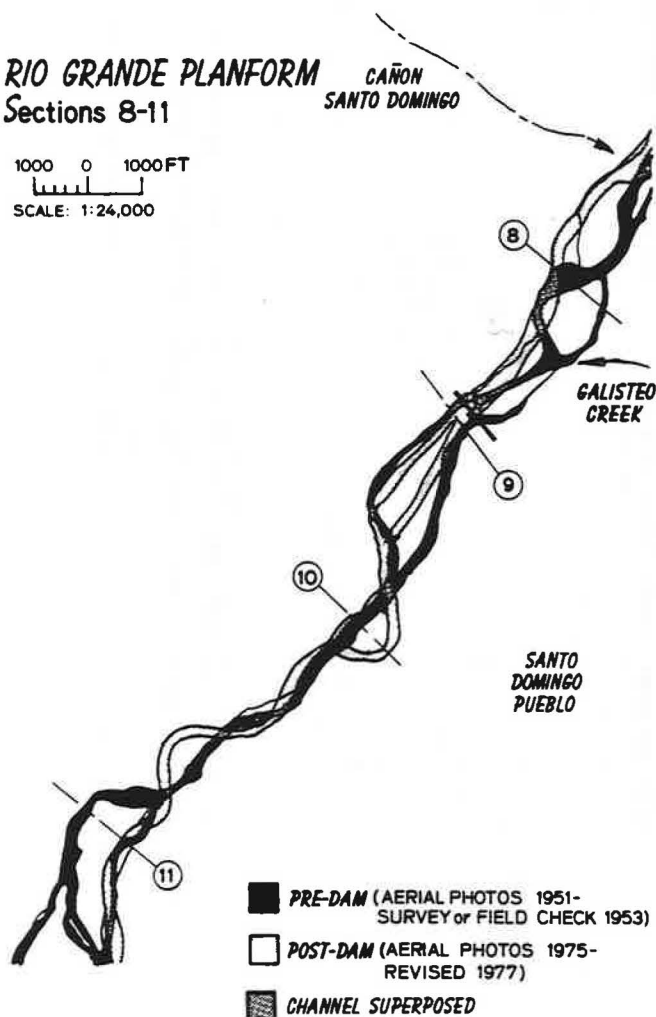


Figure 4. Pre-dam to post-dam planform comparison, cross sections 8 through 11.

stream. From that point to cross section 37 the general trend between 1971 and 1979 was a lowering of bed elevation through degradation. An anomalous reach showing aggradation can be seen between cross sections 23 and 24 which includes the Angostura Diversion and the Jemez River. Aggradation also occurred at the lower end of the study reach between cross sections 37 and 38, above the Isleta Diversion. Considering the expected response of an alluvial channel to dam construction, that is, development of a degradational wedge below the dam, the response of the reach just below Cochiti Dam is puzzling. However, a similar geomorphic response was documented below Elephant Butte Dam during the period 1917-32 where degradation was limited by development of an armor layer. Based on data from other river systems, the degradation experienced in the middle sections of the Cochiti to Isleta reach would be expected. Aggradation in the vicinity of cross section 38, at the lower end of the study reach, is an indicator that the heavy sediment load derived from upstream degradation could not be carried beyond this point. The reduced gradient in a downstream direction, depletion of main-channel flows by successive irrigation diversions, and the base-level control of the Isleta Diversion would all contribute to aggradation in this reach.

The detailed profile plots (figs. 7-10) expand the vertical (elevation) scale sufficiently to permit observation of incremental

RIO GRANDE PLANFORM Below Section 38

1000 0 1000 FT
SCALE: 1:24,000

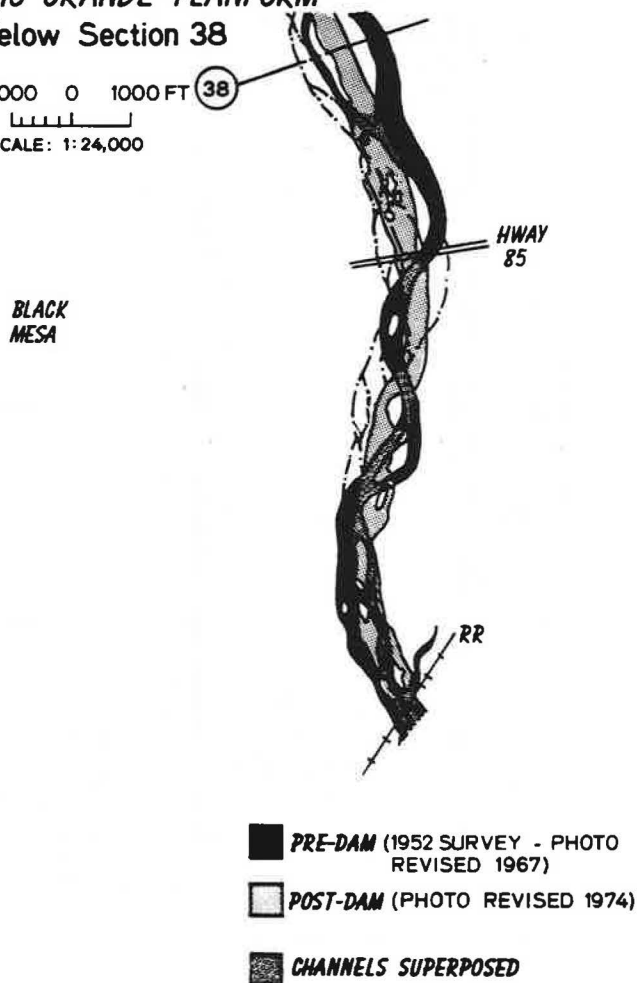


Figure 5. Pre-dam to post-dam planform comparison above Isleta Diversion.

change between May 1971 to July 1979, and extend the comparison through January 1980. During the pre-dam period (May 1971 to June 1973), aggradation continued for 14.5 km (9 mi) below Cochiti to cross section 10 (figs. 7 and 8), but from here through cross section 38 the general pre-dam trend was degradation, except for a short reach below the Jemez River and a longer 9.7-km (6-mi) segment between cross sections 31 and 34. Apparently, the stabilization and rectification of the floodway channel between 1954 and 1962 had, by the early 1970's, begun to accomplish the desired effect of reversing the long-term aggradational trend and lowering bed elevations.

The immediate response to dam construction (during the two-year interval November 1973 to November 1975) was one of degradation in the reach between Cochiti Dam and Galisteo Creek, reversing the pre-dam trend toward aggradation. Below Galisteo Creek the immediate response to dam construction was aggradation, in some cases to a level above the early pre-dam bed elevations of May 1971. With general scour of the reach just below Cochiti selective deposition would be expected downstream. There is some evidence, in the form of sequential subreaches of deposition and scour (fig. 8, mile 8 to 11), that bed material derived from scour below the dam moved downstream as "waves" or "slugs" of sediment. In general, these waves of sediment tend to accumulate in the reach above the Isleta Diversion.

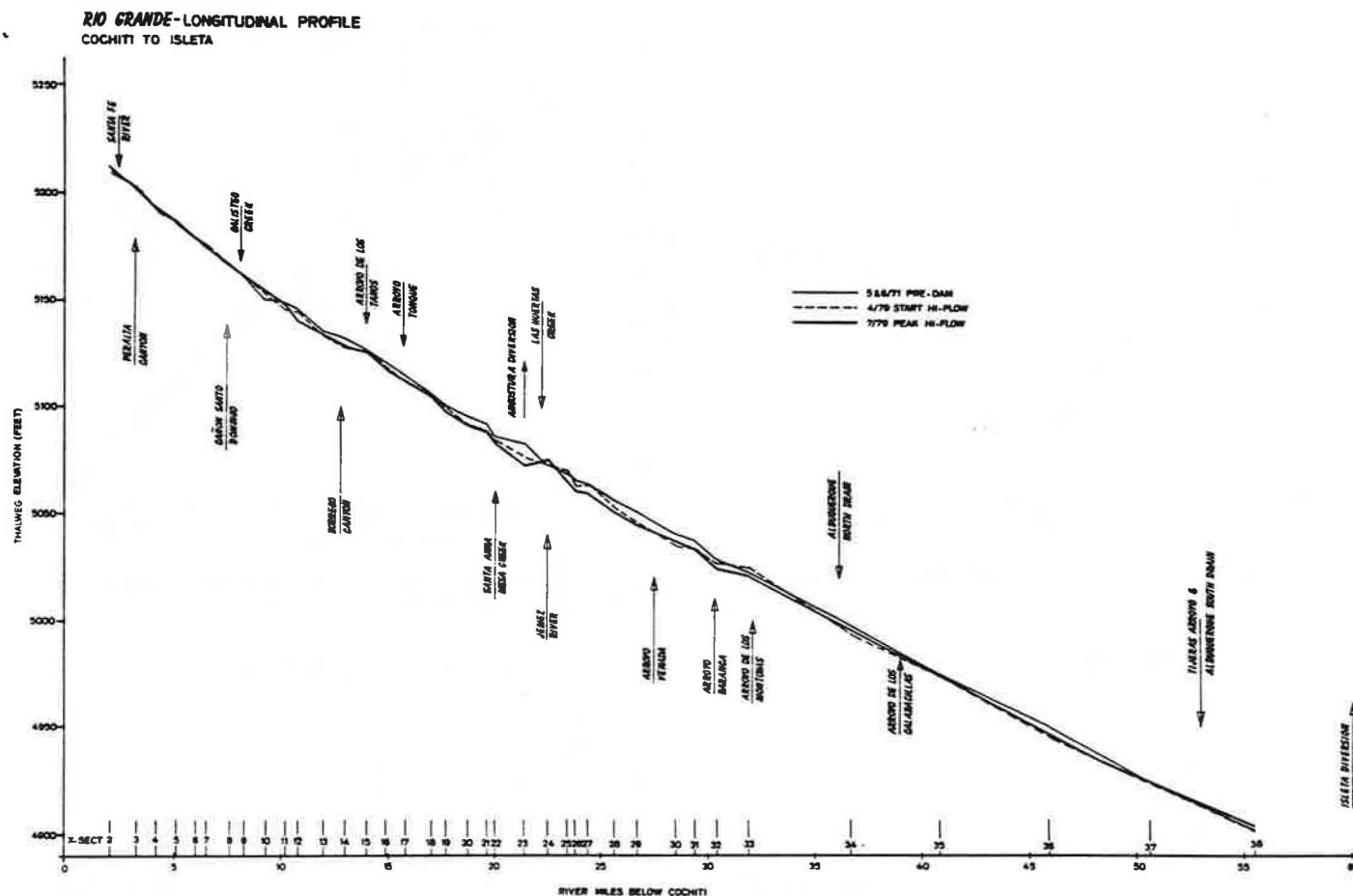


Figure 6. Pre-dam to post-dam longitudinal profile comparison, overview of Cochiti to Isleta reach. Location of cross sections and major arroyos and tributaries also shown.

The April and July 1979 surveys bracket a period of the highest peak, mean, and minimum monthly flows since the closure of Cochiti Dam (fig. 3). Field reconnaissance during the period indicated that the sustained high flows of April-July 1979 may have produced the greatest geomorphic response in the system since dam closure. Comparison of the April and July 1979 thalweg profiles with the November 1975 conditions confirms observations made in the field. This period of high flow generally induced significant, progressive degradation in the Cochiti to Isleta reach; however, the upper and lower ends of the reach responded somewhat unexpectedly, and the cross section 24 reach at the Jemez River confluence experienced significant aggradation. In the 13 km (8 mi) from Cochiti to Galisteo Creek the sustained high flow period of 1979 induced at most 0.46 m (1.5 ft) of degradation (figs. 7 and 8). The most significant response occurred at cross sections 10 and 12, with 1.4 m (4.5 ft) and 2.1 m (7 ft) of degradation, respectively. Below cross section 12 thalweg bed elevations were generally lowered to no more than 1.2 m (4 ft) downstream through cross section 33 where, again, aggradation became the dominant response. At the Jemez confluence an initial period of degradation on the rising limb of the summer 1979 flood hydrograph was followed by almost 0.9 m (3 ft) of aggradation between the April survey and the flood recession in July. Except for scour at the Jemez River confluence, the January 1980 survey indicates that the return to normal regulated flows after the April-July 1979 flood generally reworked the Rio Grande channel and refilled many of the reaches of extreme flood degradation.

Cross-Section Analysis

Compilation of cross-sectional data will normally reveal changes in such geomorphic parameters as surface width, bed elevation, average depth, and channel shape. For example, at cross section 2 (fig. 11) just below Cochiti the sequence of pre-dam aggradation followed by post-dam degradation noted on the profile plots is clearly visible. Although a visual survey of cross section plots provides some information to supplement planform and profile comparisons, the variability in bed elevation and thalweg location in a given cross section make it difficult to obtain an accurate picture of cross-sectional trends by visual observation alone. Accordingly, cross sections were planimetered to provide detailed cross-sectional data for comparison. Cross-sectional areas were measured below a fixed elevation (generally top bank elevation) for all six survey periods.

All the cross-section data are combined in Figure 12 to show pre-dam to post-dam percent change in cross-sectional area with distance along the Cochiti to Isleta reach. At each cross section the average area of the two pre-dam surveys is compared with the average area of the four post-dam surveys as a percent change (+ or -) from the pre-dam survey value. Tributary, arroyo, and diversion locations are also shown in Figure 12. Several cross sections have exhibited major changes in cross-sectional area with the transition from pre-dam to post-dam flow conditions (cross sections 8, 11, 22, 34, and 37), while others have maintained an almost constant cross-sectional area (sections 3, 7, 9, 14, and 27). For this

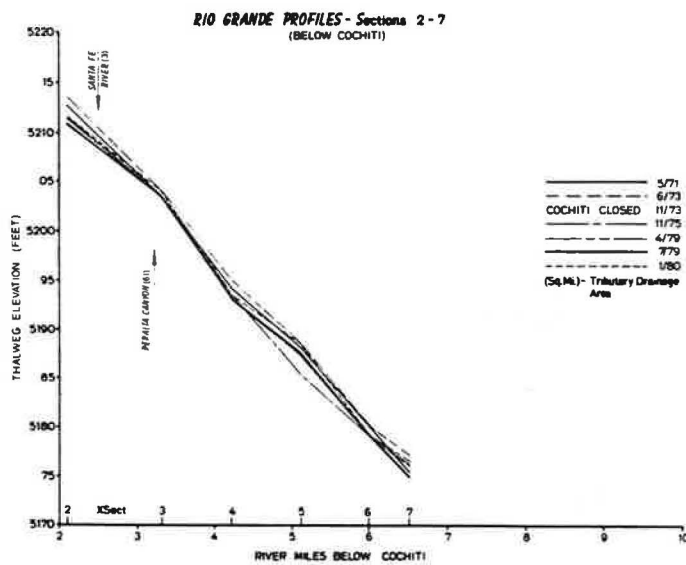


Figure 7. Detailed longitudinal profile comparison, cross sections 2 through 7 below Cochiti Dam.

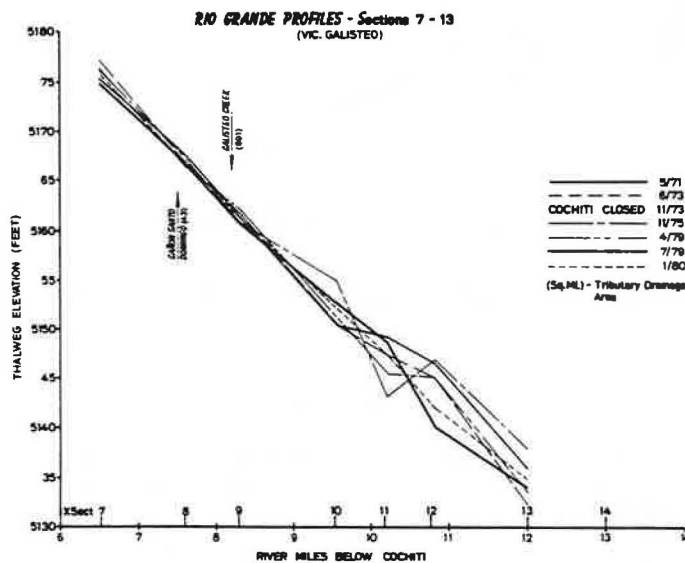


Figure 8. Detailed longitudinal profile comparison, cross sections 7 through 13 in the vicinity of Galisteo Creek.

comparison a cross section with less than 12 percent increase in area from pre-dam to post-dam conditions is considered a "stable" section. Those cross sections with a greater increase in area are considered relatively unstable. The stable cross sections have apparently been able to "resist" the general tendency toward post-dam degradation and consequently have not enlarged their cross-sectional area significantly. The trend toward increased cross-sectional area for the entire Cochiti to Ileta reach in the post-dam period is apparent in Figure 12. It is also evident that the "stable" channel cross sections are not distributed randomly through the study reach, but are grouped in the upper portions of the reach.

Sediment Characteristics

The USGS hydrologic-data report (Dewey and others, 1979) and field notes from subsequent cross-section surveys are primary sources of sediment data. Based on observations during the sam-

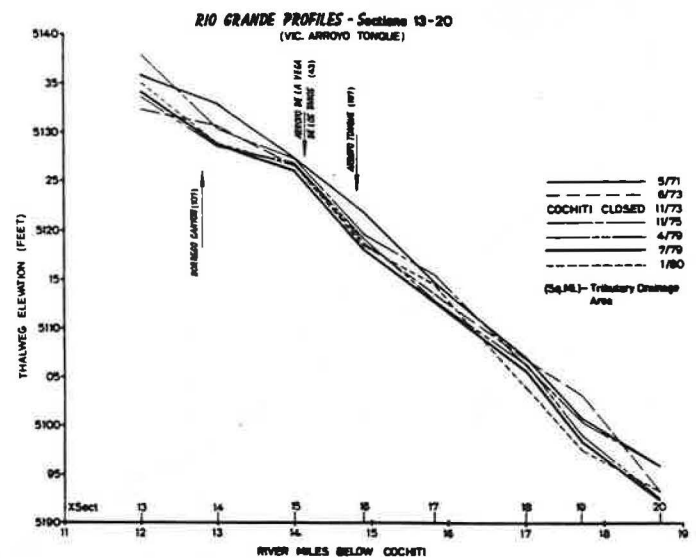


Figure 9. Detailed longitudinal profile comparison, cross sections 13 through 20 in the vicinity of Arroyo Tonque.

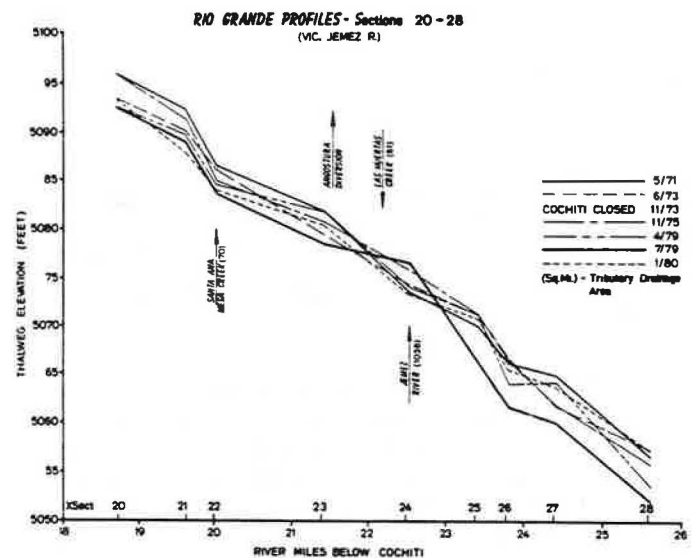


Figure 10. Detailed longitudinal profile comparison, cross sections 20 through 28 in the vicinity of the Jemez River.

pling runs, an armor layer developed rapidly in the reach immediately below Cochiti following closure of the dam. It was reported by Dewey and others (1979) that "downstream from the dam to cross section 3 most of the sand-size material, up to approximately 1 mm, was eroded from the active channel bed in the first two months following dam closure in 1973." By 1979 one of the most striking aspects of a reconnaissance below Cochiti was the quantity of gravel-size armoring material to be seen on the bed, bars, and banks of the Rio Grande as far downstream as the San Felipe reach. In the latest survey of September 1980 gravel bars and armoring were noted as far downstream as the Albuquerque reach.

Observations and sampling confirm that the armor layer that has developed below Cochiti exhibits most of the typical characteristics documented for other alluvial systems (fig. 19b). That is, less than a single complete covering layer of the larger gravel particles provides a total armoring effect for a particular discharge, and the

armor layer develops a natural filter between the larger surface particles and the subsurface material. It must be concluded that, as with other alluvial systems, a relatively thin armor layer, or veneer, of gravel now plays a key role in stabilizing the bed, bars, and islands of the Rio Grande below Cochiti.

Figure 13 documents the change with time and distance downstream of the median diameter of surface bed material from 1970 to 1975. The immediate post-dam samples are consistently coarser for the entire Cochiti to Isleta reach, with the greatest increase in bed-material size from just below the dam through the cross-section 13 reach, 19 river km (12 river mi) below Cochiti. At Peralta Canyon (cross section 3), for example, the median diameter of surface bed material increased by a factor of 5 in the immediate post-dam period, and at cross section 9 the post-dam bed material was almost 3 times coarser than pre-dam samples. Figure 14 extends this comparison another 5 years to 1980 and shows a continued coarsening of the bed surface (note the change of vertical scale). Over the ten-year period the median diameter of surface bed material increased by more than a factor of 20 at the Peralta Canyon confluence, and the "front" of significant coarsening of the bed extended through cross section 22 below San Felipe, 13 river km (8 river mi) further downstream than its 1975 position.

While an increase in the median diameter of surface bed material

is an indicator of general coarsening of the bed material and the potential for developing an armor layer, the change in the total gradation of the bed material is also important. Figures 15 and 16 are time-sequenced gradation curves for surface bed material at

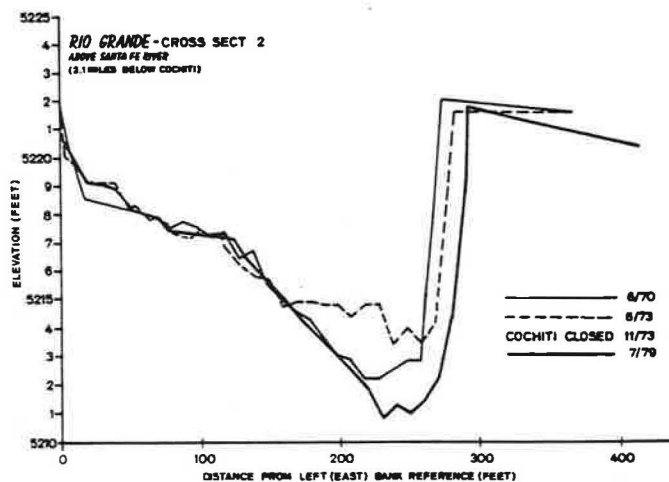


Figure 11. Pre-dam to post-dam cross section comparison, cross section 2 above the Santa Fe River.

RIO GRANDE - CROSS SECTION AREA COMPARISON

(COCHITI TO ISLETA REACH)

PRE-DAM TO POST-DAM CHANGE IN AVERAGE CROSS SECTION AREA

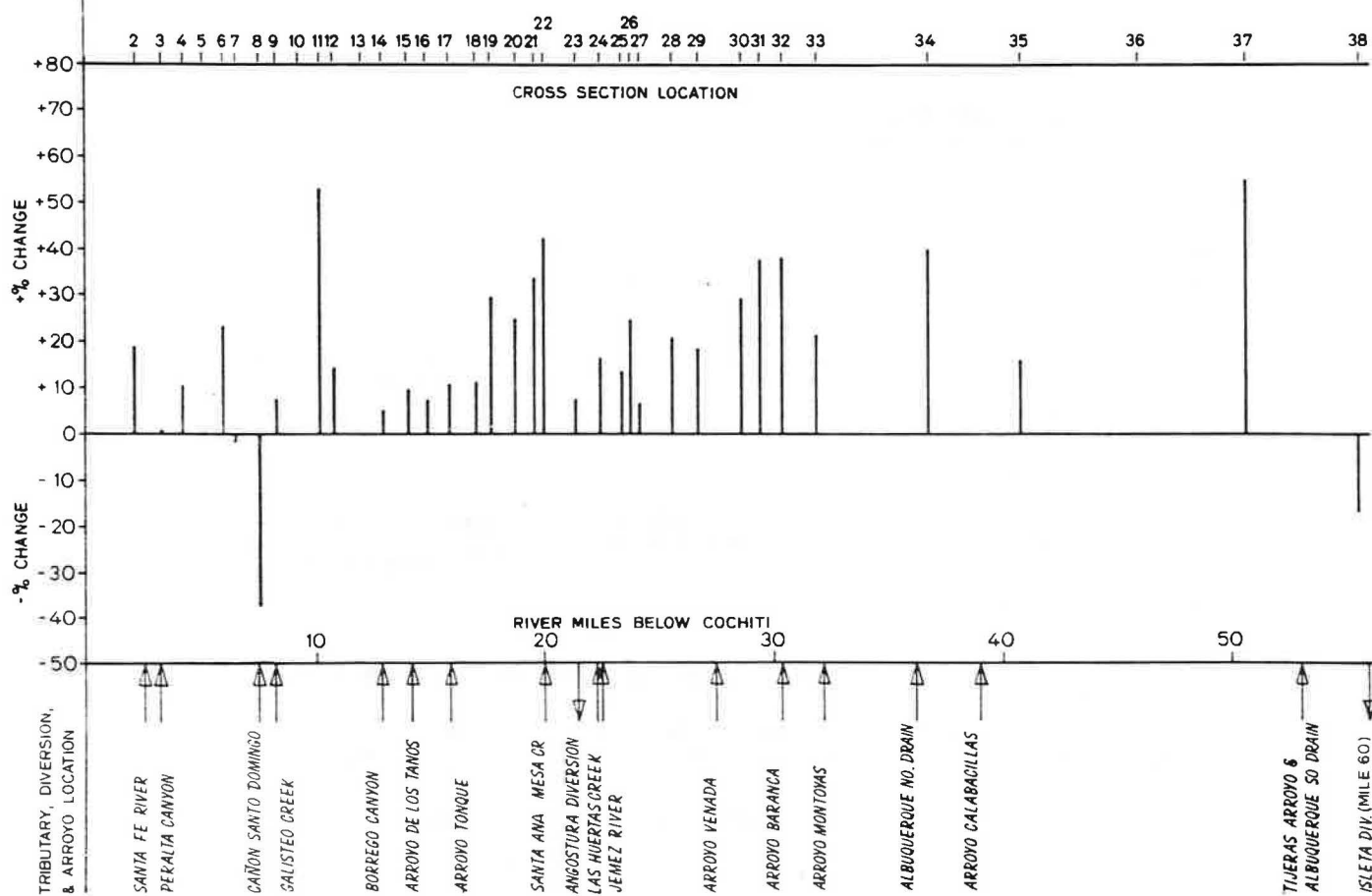


Figure 12. Pre-dam to post-dam change in average cross-sectional area, Cochiti to Isleta reach. Location of major arroyos and tributaries also shown.

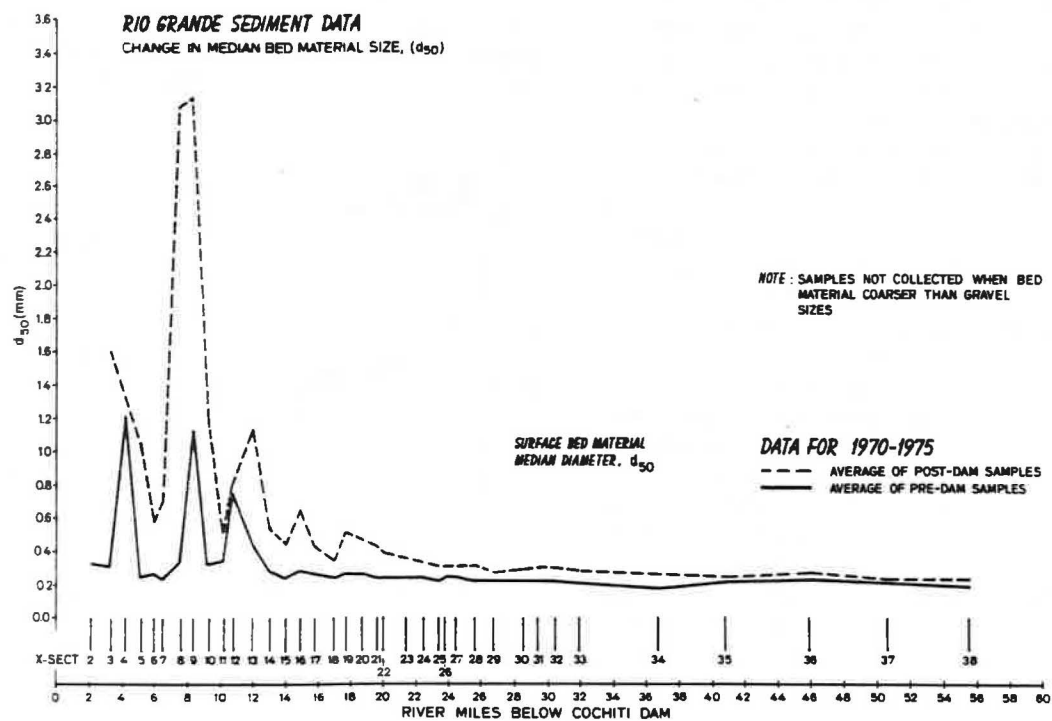


Figure 13. Pre-dam to post-dam change in average bed-material size for the period 1970 to 1975.

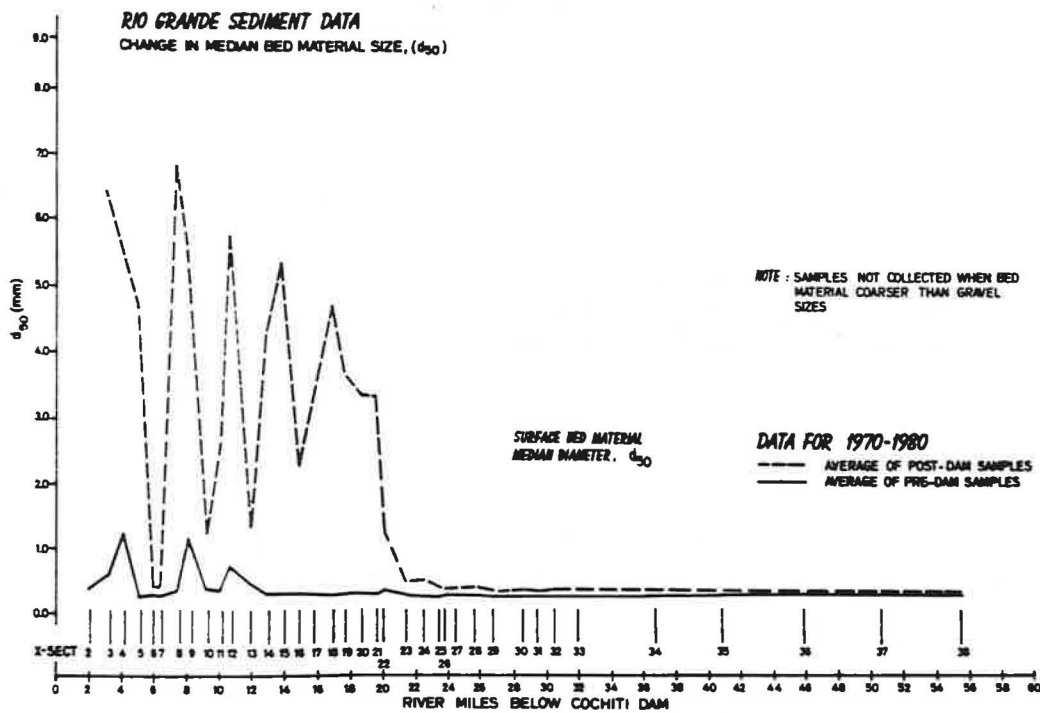


Figure 14. Pre-dam to post-dam change in average bed-material size for the period 1970 to 1980.

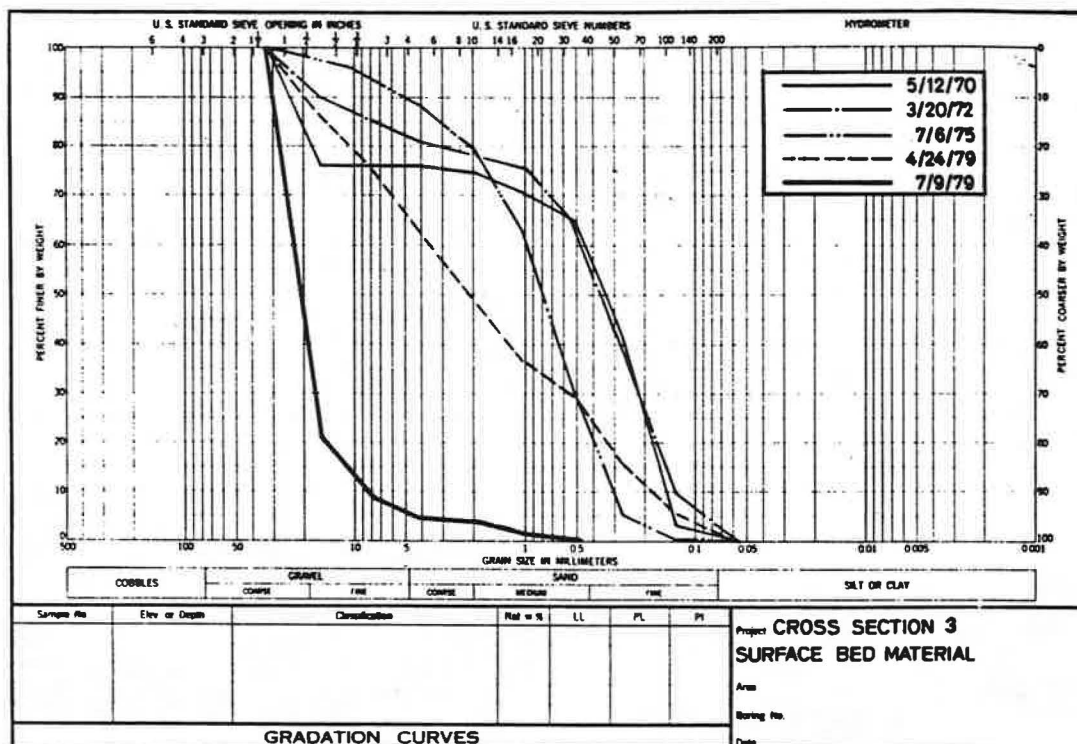


Figure 15. Time-sequenced gradation curves of surface bed material at cross section 3 below Cochiti Dam.

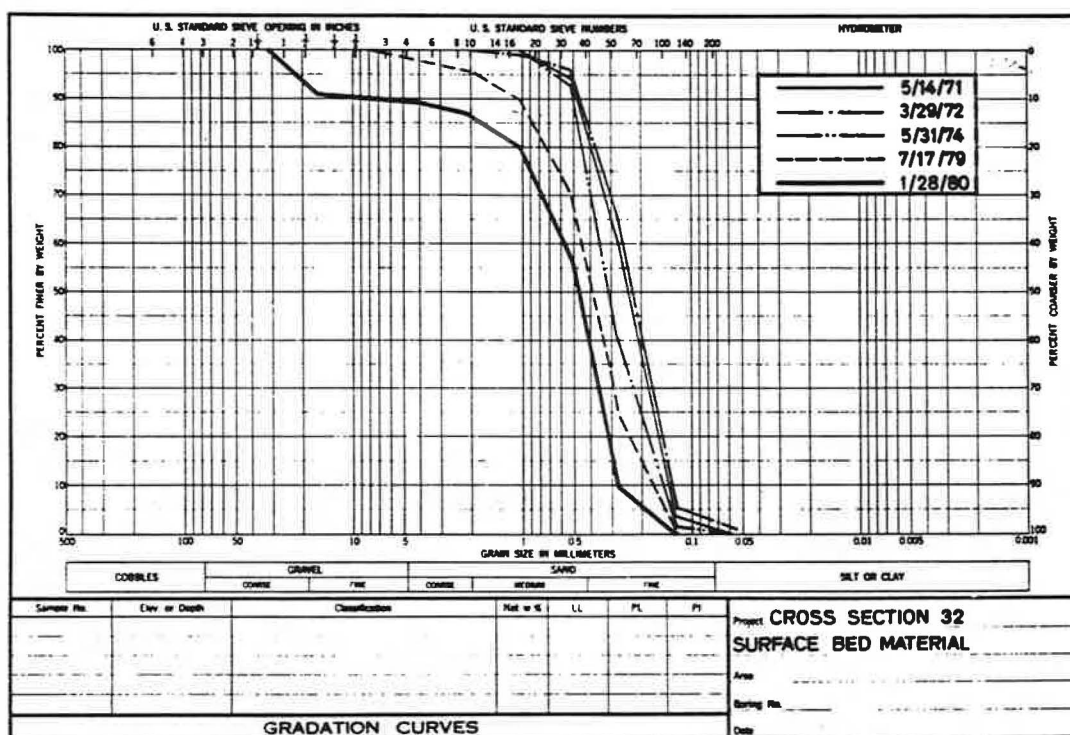


Figure 16. Time-sequenced gradation curves of surface bed material at cross section 32 above Albuquerque.

two cross sections in the Cochiti to Isleta reach. The gradation curves show an increase in the surface bed-material size for all size fractions in the post-dam period. At cross section 3 in the vicinity of Peralta Canyon, the surface bed material became progressively coarser following dam construction, with the most significant increase in size throughout the gradation during the April to July 1979 flood period. The d_5 at this location is now in the fine-gravel size; that is, only 5 percent by weight of the surface bed material is finer than gravel size. From the earliest pre-dam survey (May 1970) to the latest post-dam survey (July 1979) the median diameter (d_{50}) at this location increased from 0.32 mm to 20 mm.

For the cross sections below the Jemez River confluence (fig. 16) the increase in bed-material size is not as significant, but a progressive increase did extend through the bed material gradation.

As noted by Schumm (1977) a small fraction of the bed material, perhaps the coarsest 1 percent, can significantly control the behavior and morphology of an alluvial channel through the development of a gravel armor or veneer. The surface bed-material samples from the Cochiti to Isleta reach contain sufficient gravel to produce an armor layer through, at least, the cross section 32 reach.

Visual evidence of coarsening of the main-stem bed material and armoring below Cochiti is also available from photographic coverage during the initial and supplemental surveys. Figure 17 contains two views of the cross-section 2 reach immediately below Cochiti Dam. Rapid development of an armor layer in the immediate post-dam period was noted during the early surveys and can be seen in the comparison of Figures 17a and 17b taken in November 1973



a. November 1973, looking downstream.



b. October 1974, looking downstream.

Figure 17. Pre-dam to post-dam comparison of surface bed material at cross section 2 below Cochiti Dam.



a. September 1973, looking downstream.



b. February 1980, looking downstream.

Figure 18. Pre-dam to post-dam comparison of surface bed material at cross section 9 below the Santo Domingo Bridge.

and October 1974, respectively. By September 1979 the gravel veneer extended onto the banks in the cross-section 2 reach. Similarly, only a small quantity of gravel can be seen on the surface at cross section 9 just below the Santo Domingo Bridge in September 1973 (fig. 18a). By February 1980 gravel bars dominated the reach below the bridge and an extensive gravel layer had developed over the bed and banks (fig. 18b).

Perhaps the most significant recent post-dam change in main-stem bed characteristics has occurred at Arroyo de la Baranca (cross section 32) which carries the runoff from 26 km² (10 mi²) of drainage area to the west bank of the Rio Grande near Corrales, 48 river km (30 river mi) below Cochiti. Through the January 1980 supplemental survey this cross section was typical of the wide, shallow, sand-bed configuration of the lower end of the study reach. However, between January 1980 and the most recent survey of September 1980 a major gravel bar which includes material up to cobble size has developed at the Arroyo de la Baranca confluence. Figure 19a shows the volume and extent of the gravel deposit at the Arroyo de la Baranca confluence. Details of the armor layer can be seen in Figure 19b and are similar to the characteristics of the gravel armor that developed in the upper portions of the study reach shortly after closure of Cochiti Dam. The Rio Grande below the Jemez River was considered a typical sand-bed stream prior to closure of Cochiti Dam. The development of sand-gravel reaches more than 13 river km (8 river mi) below the Jemez River implies a major change in the hydraulic response of the system.

ASSESSMENT OF RESPONSE

In the previous section of this paper the Rio Grande below Cochiti Dam was analyzed, separately, in each of the three dimensions: planform, profile, and cross section. In this section the results of that analysis will be combined to produce a three-dimensional view of response of the Rio Grande to dam construction. The history of engineering activity in the Cochiti to Isleta reach, as well as the hydrologic record and sediment characteristics documented in the analysis section, are essential elements of this synthesis.



a. Looking west up Arroyo de la Baranca at confluence.



b. Details of gravel armor at Arroyo de la Baranca confluence. Key case for scale.

Figure 19. Arroyo de la Baranca, a west bank arroyo in the vicinity of cross section 32 (above Albuquerque), in September 1980.

Tributaries, Arroyos, and Main-Stem Stability

Perhaps the most significant observation to emerge from the geomorphic analysis is the extent to which tributaries and arroyos influence the planform, profile, and cross section of the post-dam Rio Grande below Cochiti Dam. Regulated flows of the post-dam period generally are not capable of transporting the coarser sediment load and volume of material carried to the main-stem by tributaries and arroyos. Deltaic deposits are sufficiently stable to influence main-stem planform, to create reaches of base-level control along the main-stem, and to influence the processes of aggradation and degradation below Cochiti Dam. The effect is so pronounced that one can predict with some certainty that an arroyo contributing sediments from more than a 155-km² (60-mi²) drainage area will exercise some control over main-stem channel characteristics. This applies almost without exception between Cochiti and the Jemez River. However, the recent development of a large gravel bar and channel armoring at Arroyo de la Baranca (26-km² [10-mi²] drainage area) implies that additional factors need to be considered when assessing arroyo and tributary influence on the main-stem. These might include arroyo slope, characteristics of the sediment sources in the contributing area, and the hydrologic history of the drainage area, particularly the occurrence of extreme events.

Comparison of planform change below Cochiti indicates that where arroyos and tributaries deposit sediments beyond the competence of regulated main-stem flows, the Rio Grande channel was forced away from the tributary outlet through erosion of the opposite bank (see, for example, the response at Galisteo Creek, fig. 4). At some locations channelization may have initiated or accelerated this response. Conversely, where sediment supplies are reduced by engineering activity, as with the diversion of the Santa Fe River by Cochiti Dam, the Rio Grande channel can migrate into the tributary delta.

The influence of tributaries and arroyos on main-stem stability is most evident in the plots of longitudinal thalweg profiles. Considering the vertical dimension, the net variation in the thalweg profile plots is an indicator of stable (or unstable) regions. Between

Peralta Canyon and Galisteo Creek, the reach immediately below the dam, the profile plots form a tight envelope with a net variation of less than 0.6 m (2 ft) (figs. 7 and 8). Below Galisteo Creek (cross section 9) the envelope of thalweg elevations varies by as much as 2 m (7 ft) through cross section 15, where Borrego Canyon and Arroyo Tonque bracket a reach of strong base-level control (fig. 9). The pattern is repeated between cross sections 16 and 24 with a maximum variation of 1.8 m (6 ft) until the Jemez River again limits base-level response (fig. 10). During the study period arroyos below the Jemez River did not appear to influence base-level stability on the main-stem; however, the development of the gravel bar at Arroyo de la Baranca between January and September 1980 may portend an increasingly important role for arroyos in the lower portion of the study reach as the influence of Cochiti Dam progresses downstream.

The response in profile of the Rio Grande below Cochiti underscores the inadequacy of methods currently available in the literature for predicting degradation below dams. While most investigators recognize the limiting effects of channel armoring, and many reference the importance of tributaries, the problem is so complex that analytical techniques currently provide the means of predicting response only as some variation of the "classic" degradational wedge. Bank erosion, discharge variability, meandering, and sediment inflow from tributaries all affect channel response below dams, but available techniques do not address response in the complex environment implied by these variables. The most promising approach to this complex problem is physical-process computer modelling. The verified results from current applications indicate that the routing of sediment by size fraction with computer simulation modelling will permit the effects of armoring, altered channel geometry, discharge variability, and sediment inflow from tributaries to be included in the analysis of channel response below dams.

Plotting of cross-sectional data as a pre-dam to post-dam percent change in cross-sectional area (fig. 12) provides another view of the relationship of tributaries and arroyos to the stability of the main-stem Rio Grande. From this comparison it is apparent that a number of cross sections have been able to resist the general post-dam trend toward degradation and resist the enlarging of their cross-sectional area. It is also evident that these stable channel cross sections are not distributed randomly through the reach. In terms of the influence of a tributary or arroyo delta on the main-stem, backwater effects decrease the gradient above the delta and induce deposition, while the increased gradient below the delta transports coarser sediments into the reach immediately downstream. There is, then, a range of influence of tributary and arroyo deltas that extends beyond the point of confluence.

Based on this cross-sectional criteria for stability, there is a strong correlation between arroyo or tributary location and stable channel sections in the upper half of the Cochiti to Isleta reach. The cross-sectional area at Peralta Canyon has remained essentially constant in the pre- to post-dam period. Yet, Peralta Canyon is located just below Cochiti Dam where degradation theory would predict the most significant response. Cross section 4, less than 1.6 km (1 mi) below Peralta Canyon, is apparently within the range of influence of coarse sediments derived from that tributary and has experienced only a slight increase in cross sectional area in the post-dam period.

Galisteo Creek has also influenced upstream and downstream cross sections. The range of influence of Galisteo Creek extends from cross section 7 (upstream) to cross section 9 (downstream). At cross section 8, just above the confluence, a major decrease in

cross-sectional area is indicative of the ability of sediment inflow from Galisteo Creek to dominate main-stem processes. Another sequence of stable channel cross sections begins at Borrego Canyon, 8 km (5 mi) below Galisteo Creek, and extends through the Arroyo Tonque reach. From Arroyo Tonque to the Angostura Diversion there is an 8-km (5-mi) reach with no major inflowing arroyos or tributaries, and cross sections in this reach have shown significant increases in cross-sectional area in the post-dam period.

Changes in sediment characteristics in the post-dam period have been analyzed primarily to assess the extent to which degradation below Cochiti was accompanied by development of an armor layer. Observations and analysis reveal that an armor layer developed rapidly in the reach below the dam, and armoring progressed downstream in the years following dam closure. Regions of the most significant increase in bed-material size correlate reasonably well with arroyo or tributary locations such as Peralta Canyon, Galisteo Creek, and Borrego Canyon, indicating a relationship between tributary inflow and material available for armoring (figs. 13 and 14).

At Peralta Canyon, for example, the median diameter of the surface bed material increased significantly during the 10-year study period. Following the April-July 1979 flood, 95 percent by weight of the surface bed material at the Peralta Canyon confluence was in the gravel, or larger, size range. Below Borrego Canyon a similar progression in surface bed-material size occurred. Data from the 1970 to January 1980 period do not show a similar correlation between increased bed-material size and tributary location below the Jemez River. However, the development of the major gravel bar at the Arroyo de la Baranca confluence indicates that the response of the lower half of the study reach may eventually parallel that of the upper half.

The geomorphic analysis of planform, profile, cross-section, and sediment data from the Cochiti to Isleta reach supports the conclusion that sediment inflow from arroyos and tributaries has dominated the response of the main-stem Rio Grande to altered conditions of flow and sediment discharge following closure of Cochiti Dam. Regulated flows of the post-dam period generally are not capable of transporting the coarser fractions or volume of material carried to the main-stem by many tributaries and arroyos. Above the Jemez River deltaic deposits are sufficiently stable to influence main-stem planform, to create reaches of base-level control, and to influence the processes of aggradation, degradation, and armoring. Recent evidence indicates that arroyos and tributaries below the Jemez River will play an increasingly important role in main-stem processes as degradation and armoring progress downstream.

The Impact of Sediment Detention

From an aerial view, the large sandy delta at the Jemez River confluence is one of the most striking features of the Rio Grande in the Cochiti to Isleta reach. Below San Felipe and the Angostura Diversion the Rio Grande turns to the west and flows along the base of the mesa, then is deflected in a gradual curve by the Jemez River delta. Historically, the Jemez River has carried large sediment loads to the Rio Grande. It has been estimated that 20 to 40 percent of the sand found in floodplain and channel deposits between Albuquerque and Bernardo is derived from the Jemez River. After the completion of Jemez Canyon Dam in 1953, the Jemez River continued to carry large quantities of sand-size sediment to the main-stem. Accumulated flood storage generally was completely released by early fall, and as a result, the trap efficiency of the reservoir was as low as 40 percent.

The time-sequenced plots of longitudinal profile reveal that the volume of sediment in the Jemez River delta has influenced base level of the Rio Grande in the post-dam period (fig. 10). From the early pre-dam period through the immediate post-dam period more than 0.6 m (2 ft) of sediment accumulated at the Jemez confluence (cross section 24). By April 1979 degradation had returned bed elevations in this reach to approximately the pre-dam level, but the accumulation of more than 0.9 m (3 ft) of sediment during the 1979 flood raised the bed elevation at the Jemez confluence to its highest point in the study period. The net variation of 0.9 m (3 ft) or less at cross section 24 contrasts with a range of 2 m (7 ft) in upstream reaches and more than 1.8 m (6 ft) in downstream reaches during the same period, evidence of some control of base level by the volume of sand in the Jemez delta.

Response of the Rio Grande at the Jemez confluence during the 1979 flood period clearly illustrates the impact of sediment inflow from the Jemez River on main-stem processes. The aggradation apparent at the Jemez confluence (fig. 10) can be attributed to the correlation of releases of flood storage between Cochiti Dam and Jemez Canyon Dam in the April to July 1979 period. Decreased inflow at Cochiti permitted comparatively large releases from Jemez Canyon Dam in early May. These peak flows scoured much of the 4.8-km (3-mi) reach of the Jemez River below the dam and converted the sand-bed channel to a gravel/cobble riffle and pool sequence (fig. 20). Sediment derived from channel scour produced the significant increase in bed elevation at the Rio Grande confluence documented during the July 1979 survey.

In summer 1979 a permanent pool was established in the Jemez reservoir, and the normal early fall release of flood storage did not take place. As of the January 1980 supplemental survey, bed elevations at the Jemez confluence had been reduced to their lowest point in the 10-year study period by scour during the normal regulated flows of the post-flood period. As sediment was removed from the Jemez delta, significant aggradation occurred in the Rio Grande channel as far downstream as cross section 33, 13 river km (8 river mi) below Cochiti. This rapid post-flood degradation at the Jemez confluence must have been accelerated by the establishing of a permanent pool in Jemez reservoir and the cutoff of the sediment supply from that source.



Figure 20. Looking up the Jemez River toward Jemez Canyon Dam from the gaging station (September 1980).

Plotting of the selected thalweg elevations from the September 1980 supplemental survey shows that degradation has continued at cross section 24, and bed elevation is now at its lowest point in the 10-year study period. Without replenishment of sediment from the Jemez River source, degradation has progressed downstream for more than 21 km (13 mi) and has worked upstream to and above the Angostura Diversion. In August 1980 thalweg elevations almost 3.2 km (2 mi) above the diversion were more than 0.8 m (2.5 ft) below the lowest elevation of the study period.

The May 1979 to August 1980 sequence of aggradation and degradation at the Jemez confluence provides graphic evidence that the base level of the main-stem Rio Grande is extremely sensitive to not only coarse material carried in from steeper arroyos, but also to a large volume of finer material contributed by a major tributary. Project objectives for Cochiti Dam included reversing the long-term trend toward aggradation on the Rio Grande and inducing degradation. The response at the Jemez confluence indicates that sediment detention on arroyos and tributaries can contribute to those objectives. However, the dominant role of sediment inflow from arroyos and tributaries in controlling the planform, base level, and channel cross section of the post-dam Rio Grande also implies that a decision to establish a permanent pool at an existing dam or to construct additional sediment detention dams must be carefully considered. For example, sediment detention at Peralta Canyon, Galisteo Creek, or Borrego Canyon, singly or in concert, could have a significant impact on alluvial channel stability and the stability of structures in the Cochiti Dam to Jemez River reach.

Trends in River System Stability

From the Elephant Butte Dam analysis it was apparent that during the first 15 years of reservoir operation a complete adjustment to altered conditions of flow and sediment transport was not achieved, except in the reach immediately below Elephant Butte Dam where natural armoring limited further response. It is highly unlikely that in the 7 years since closure of Cochiti Dam total system response has been achieved. Accordingly, this section of the paper addresses trends in the river-system stability below Cochiti Dam. Where previous portions of this section have assessed the specific influence of tributaries, arroyos, and sediment detention on the Rio Grande, this sub-section is concerned with such system-wide processes as sediment movement and response to high-stage flow in the post-dam period.

The pre-dam to post-dam analysis of river position and river form reveals some lateral movement and change in planform characteristics between Cochiti and San Felipe, and only limited out-of-channel change between San Felipe and Angostura. Below Angostura all variations in planform have taken place within a well-defined floodway channel with banklines established and controlled by multiple lines of jack fields, heavy bosque vegetation, and levees. Field observations during the April to July 1979 sustained high flow and examination of color infrared photography taken in April 1979 reveal active, but local, planform adjustment as far downstream as the Albuquerque reach.

Bank cutting occurred on the outside of most large meander bends as evidenced by undercutting of vegetation along the bankline and flow into and behind the jack fields. Except for these areas, however, the stability of the channel pattern established during the regulated low-flow period from 1974 to 1978 was surprising. Rather than gradually changing to a typical high-flow channel pattern, the Rio Grande below Cochiti responded to the first high-flow period following dam closure by holding and incising the low-flow channel pattern. Understanding this puzzling response,

which caused some concern as releases from Cochiti exceeded $142 \text{ m}^3/\text{s}$ ($5,000 \text{ ft}^3/\text{s}$) and the channel continued to hold its low-flow position, requires an understanding of the typical response of an alluvial channel to high- and low-stage flows.

Because of the influence of stage on channel morphology, an alluvial river should be reviewed as two distinct rivers flowing in a single riverbed. The low-stage river and the high-stage river each has its own character, its own bed forms, its own system of meanders, and its own geometric parameters such as width and depth. The system of channels formed by, and adapted to, the flow conditions of the low-stage river is generally destroyed by the flows of the high-stage river. As stage falls again, the low-flow stream must reform its own channels through the maze of islands, bars, and channels that do not conform to its character and capacity.

It is evident that during the extended low-flow period on the Rio Grande following dam closure at Cochiti, the well-developed gravel armor above Angostura as well as stabilization of point bars and closure of chute channels by vegetation through the Albuquerque reach "locked" the Rio Grande into the low-flow channel pattern. It was not until flows exceeded $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) that the river was able to break through the gravel armor and vegetation on islands, bars, and banklines. As flows increased from $142 \text{ m}^3/\text{s}$ ($5,000 \text{ ft}^3/\text{s}$) toward $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) some remedial measures were necessary to protect levees adjacent to the outside of meander bends, but once the high-flow pattern had been established, engineering measures to protect the bankline were no longer required.

It is interesting to note that $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) was considered the "dominant" or channel-forming discharge of the middle Rio Grande in the pre-dam era (Schembera, 1963). Response below Cochiti during the 1979 flood period supports the conclusion that flows in this range continue to have "channel-forming" capacity in the post-dam period. To reduce the impact of a sustained low-flow period and preclude development of a locked-in channel pattern, consideration should be given to periodic "flushing" of the system below Cochiti. If it is possible within the constraints of operational rules, irrigation demand, and compact agreements, releases from Cochiti in the range of $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) should be scheduled annually.

In regard to channel stability in planform, the jetty fields and bosque vegetation are largely responsible for the stable channel position evident below the Jemez River. Rock- or pile-supported contraction dikes have had only limited success on the Rio Grande, but Kellner jetties have been used extensively for channel stabilization. The Kellner jetty system is particularly suited to heavy silt-laden streams subject to considerable variation by channel scour during periods of high flow. These steel jetties consist of large "jacks" tied together with cable forming permeable, flexible multiple-units that conform to channel scour. They permit sediment-laden flows to penetrate the jetty fields where velocity and energy are reduced. Sediment is deposited behind the jetties and vegetation grows rapidly on the accumulated sediment, further increasing the effectiveness of the jetty fields. The system can be adapted to the protection of levees, riverbanks, and bridge abutments (Woodson and Martin, 1963).

Processes set in motion by the closure of Cochiti Dam will eventually limit the effectiveness of the existing jetty fields, and may dictate against the installation of new jetty fields for channel stabilization. Permeable jetties are effective only if there is a significant amount of debris carried by the stream, and the suspended-sediment concentration must be large so that there will be deposi-

tion in the jetty field. The general tendency toward the post-dam degradation in the Cochiti to Isleta reach and the development of armored reaches below the dam are strong indicators of a changing sediment regime below the dam and less favorable conditions for jetty stabilization. Less frequent inundation of flood-plain areas and depriving the main-stem of such major sediment-source areas as the Jemez River will also reduce the effectiveness of the jetty fields. A degradational environment and reduced sediment supply will induce scour in the jetty fields, and the existing lines of jetties could eventually be undercut and buried.

One additional factor influencing planform stability was observed during reconnaissance and survey in the reach below Cochiti. The large trees along the present Rio Grande bankline which lend stability to many reaches below Cochiti are being seriously damaged by an apparently expanding beaver community. Figure 21 provides graphic evidence of the extent of this damage and the loss of bankline stability that follows. The problem appears serious enough to warrant corrective measures. As the jack fields become a less effective device for channel stabilization, protection of the banks by vegetation becomes increasingly important.

Some of the remedial measures taken to provide temporary protection for the bankline at the outside of meander bends during the April to July 1979 "flood-fighting" period are also evident in Figure 21. These measures involved cutting trees adjacent to the threatened bankline, lacing several trees together with cable, and securing the mass of timber along the bankline with cable ties. This creates an impromptu jetty field and offers some short-term protection, but for the same reason that extensive beaver damage is a source of concern, timber cutting may create long-term problems. In addition, snags of timber that are swept downstream can block channels and create planform instability. This traditional method of flood fighting should be reconsidered in view of the decreased effectiveness of the jetty fields in the post-dam period and consequent increased importance of bankline vegetation.

Comparison of the time-sequenced plots of longitudinal profile reveals that the trends in aggradation and degradation set in motion by the closure of Cochiti Dam are extremely complex. While the overall response in the reach below Cochiti has been toward



Figure 21. Beaver damage along the west bank of the Rio Grande above cross section 8 (February 1980).

degradation, except immediately above the Isleta Diversion, sequences of aggradation and degradation, both over time and with location along the Rio Grande, have occurred during the post-dam period. Examination of the detailed profile plots provides evidence of sequential subreaches of deposition and scour, indicating that bed material derived from upstream scour moves downstream as waves or slugs of sediment. This mode of sediment transport is superposed on the points of base-level control provided by arroyos, tributaries, and diversions, but in general, these waves of sediment move downstream through the system and accumulate in the reach above the Isleta Diversion.

The Cochiti to Isleta reach will continue to respond to the closure of Cochiti Dam. Even the upstream reaches that have adjusted to the altered conditions of flow and sediment transport will experience sequences of aggradation and degradation as sediments move through the system. In this alluvial environment, stability for the Rio Grande implies some continued variation in bed elevation, channel area, and channel shape about an equilibrium or graded condition. The range of variation above Angostura will be limited by planform and base-level control provided by the armor layer and the influence of numerous tributaries and arroyos. Below Angostura the range of variation in channel parameters will diminish as degradation and armoring progress downstream. However, the lower portion of the study reach may never attain the same level of stability as the Cochiti to Angostura reach, primarily because tributaries and arroyos with a drainage area necessary to influence main-stem processes are less common below Angostura.

The response of the Rio Grande below Cochiti indicates that the upper portion of the study reach is approaching a stable condition much more rapidly than the reach below the Jemez River. In fact, with the rapid development of an extensive armor layer and base-level control by arroyos and tributaries, the portion of the study reach between Cochiti and Galisteo Creek may have essentially completed adjustment to the closure of Cochiti Dam by 1975. Degradation and armoring progressed downstream through the San Felipe reach and by summer 1979 had reached a level of stability that is yet to be achieved in the study area below the Jemez River. The recent development of a gravel armored bar at the Arroyo de la Baranca confluence above Albuquerque and the appearance of armoring material through the Albuquerque reach provide evidence that response to Cochiti Dam is continuing in the lower half of the Cochiti to Isleta reach.

CONCLUSIONS

The conclusions listed below are derived from the analysis and assessment of response of the Rio Grande to the construction of Cochiti Dam. It is worth repeating here that a qualitative geomorphic analysis will yield meaningful results, particularly in establishing trends in alluvial-system response to engineering activity and in bringing potential problem areas into focus. But qualitative analysis, alone, is generally not a sufficient basis for making engineering decisions involving major new construction or significant changes in the allocation of maintenance resources. Such decisions must be supported by more detailed quantitative analysis, incorporating as a possibility physical-process computer modelling of the alluvial system involved.

In the Cochiti to Isleta reach sediment inflow from arroyos and tributaries has dominated the response of the main-stem Rio Grande to altered conditions of flow and sediment transport following closure of Cochiti Dam. Regulated flows of the post-dam period generally are not capable of transporting the coarser sedi-

ment load and volume of material carried to the main-stem by arroyos and tributaries. Between Cochiti and the Jemez River, deltaic deposits at the confluence of tributaries and arroyos are sufficiently stable to influence planform, to create reaches of base-level control, and to influence the processes of aggradation, degradation, and armoring on the Rio Grande.

The reach immediately below the dam from Cochiti to Galisteo Creek had essentially completed adjustment to the closure of Cochiti Dam by 1975. Degradation and armoring progressed downstream through the San Felipe reach, and by summer 1979 the upper portion of the study reach had attained a level of stability yet to be achieved in the study area below the Jemez River. The Cochiti to Isleta reach of the Rio Grande will continue to respond to the closure of Cochiti Dam. Even the upstream reach that has adjusted to the altered conditions of flow and sediment transport will experience sequences of aggradation and degradation as sediments move through the system.

Recent evidence indicates that arroyos and tributaries below the Jemez River will play an increasingly important role in main-stem processes as degradation and armoring progress downstream. Response in the lower portion of the study reach will eventually parallel that above the Jemez River. However, the level of stability between the Jemez River and Isleta may never reach that of the Cochiti to Angostura reach, primarily because tributaries and arroyos with a drainage area necessary to influence main-stem processes are less common below Angostura.

Response at the Jemez River confluence supports the conclusion that the base level of the main-stem is extremely sensitive to not only coarse material carried in from steeper arroyos, but also to a large volume of finer material contributed by a major tributary. As a result, a decision to establish a permanent pool at an existing dam on a major tributary or to construct sediment-detention dams on smaller arroyos must be supported by a detailed analysis of potential response of the main-stem Rio Grande.

During the extended low-flow period following closure of Cochiti Dam, the well-developed gravel armor above Angostura and stabilization of point bars and closure of chute channels by vegetation "locked" the Rio Grande into the low-flow channel pattern. Flows in excess of $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) were required to initiate a transition to a high-flow channel pattern. To prevent the development of a channel pattern "locked in" to low-flow conditions and recurrence of problems associated with the April-July 1979 sustained high flows, releases from Cochiti Dam of about $170 \text{ m}^3/\text{s}$ ($6,000 \text{ ft}^3/\text{s}$) should be scheduled annually.

Processes set in motion by the closure of Cochiti Dam will eventually limit the effectiveness of the existing jetty fields. In the post-dam period less frequent inundation of flood-plain areas, a reduction in sediment supply from major source areas such as the Jemez River, and degradation and armoring in the upstream channel all dictate against the installation of new jetty fields for channel stabilization. As the Kellner jetties become a less effective device for channel stabilization in the post-dam period, protection of the banks by vegetation will become increasingly important. Control of the beaver community along the banklines may be required, and traditional flood-fighting techniques which involve cutting of trees along the bankline should be reconsidered.

The problem of predicting river response below a dam and the extent to which development of an armor layer will limit degradation is extremely complex. While it is recognized that bank erosion, discharge variability, meandering, and sediment inflow from tributaries affect channel response below dams, analytical techniques currently available in the literature do not address response

in the complex environment implied by these variables. Physical-process computer modelling offers the most promising approach to solving this complex problem.

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