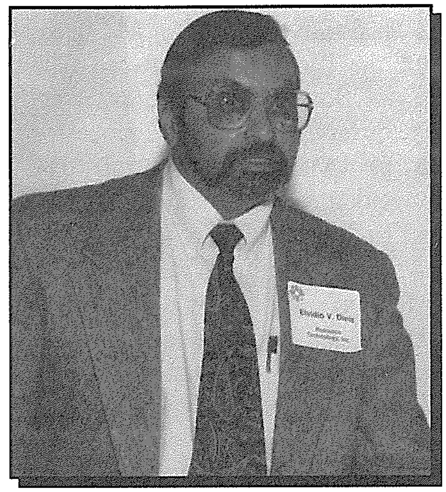
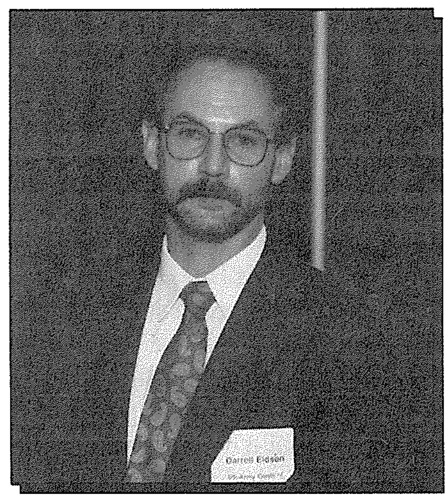
__Elvidio Diniz__ is President and Principal Engineer at Resource Technology, Inc. He has more than 30 years experience in water resources engineering analysis and design, including specialized experience in hydraulics, hydrology, erosion control, reservoir operations management, and systems analysis of dams, reservoirs and channels. He has prepared design and cost estimates for numerous water resources and civil engineering projects including water supply and conservation systems, wastewater systems, and drainage facilities throughout the Southwest and Midwest. Elvidio has a B.S. in Civil Engineering from the Catholic University of America and an M.S. in Civil Engineering from UNM, with additional course work at the University of Texas at Austin.



__Darrell Eidson__ is employed as Hydraulic Engineer, Hydrology and Hydraulics Section, U.S. Army Corps of Engineers. He began working with the Corps immediately following graduation from UNM with a B.S. in Civil Engineering and is currently pursuing a master's degree at UNM. Darrell developed a fixation with hydraulics while piloting his whitewater raft on local rivers. This interest led him to concentrate on water-resources courses during his academic studies. The Albuquerque District of the Corps saw a need for expertise in sediment related impacts on civil works projects, and Darrell is pursuing proficiency in this area.



RIO GRANDE SEDIMENT STUDY—SUPPLY AND TRANSPORT

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INTRODUCTION

The 1992 New Mexico State Legislature directed the Interstate Stream Commission (ISC) to study the feasibility of clearing and deepening the channel of the Rio Grande between Albuquerque and Elephant Butte to improve water conveyance and water conservation. The ISC requested the U.S. Army Corps of Engineers-Albuquerque District (COE) to undertake this study under the Planning Assistance to States Program.

The study was divided into two phases. Phase I consisted of an analysis of the sediment contribution to the Rio Grande from the tributaries and an evaluation of the existing U.S. Geological Survey (USGS) sediment gage data. Phase II will be an analysis, through the use of an HEC-6, *Scour and Deposition in Rivers and Reservoirs*, computer model, to determine the long-term performance of any Rio Grande channel improvements.

Phase I of the study was conducted jointly by the Albuquerque District Corps office and Resource Technology, Inc. This narrative presents the Phase I methods and results.

TRIBUTARY ANALYSIS

Procedure Overview

The study area was first extended upstream to Cochiti Dam as the upstream boundary, with Elephant Butte Reservoir as the downstream boundary. The study area sub-basins (tributary watersheds) were delineated using 1:250,000 scale maps and classified into one of three categories:

- small sub-basins (drainage area less than 80 square miles), with steep channels or arroyos
- small sub-basins, with less steep channels or arroyos
- large arroyos (drainage areas greater than 80 square miles) possessing characteristics of both previous classes

From a total of 171 sub-basins, eleven "representative" sub-basins were selected for detailed analysis. The selected sub-basins and their respective drainage areas are listed in Table 1. Their locations are shown on Figure 1. A detailed sediment analysis was then performed on each of the selected sub-basins. Finally, a regression analysis of the results was conducted to allow prediction of sediment yields from the remaining sub-basins.

TABLE 1. REPRESENTATIVE SUB-BASINS

Sub-basin Name	Drainage Area (mi^2)
Borrego Canyon	117
Tonque Arroyo	192
Las Huertas Creek	30
Arroyo Agua Sarca	26
North Pajarito Arroyo	3
Comanche Draw	101
Abo Arroyo	290
Palo Duro Canyon	69
Arroyo Los Alamos	63
San Lorenzo Arroyo	34
Arroyo del Coyote	7

Sub-Basin Detailed Analysis

Data gathered on the selected sub-basins included:

- USGS 7½ minute quadrangle maps were used for detailed sub-basin boundary delineation,
- Soil Conservation Service (SCS) Soil Survey maps were used to estimate parameter values to be used in sediment yield calculations,
- field surveys of specific arroyo reaches were performed for use in hydraulic modeling,
- sediment samples of bed and overbank material were collected to determine size gradations to be used in sediment transport calculations.

Hydrologic modeling was performed using the HEC-1, *Flood Hydrograph Package*, computer program. This provided peak discharges, runoff volumes, and runoff hydrographs. The model results were calibrated using the procedure described in the Draft USGS document *Methods for Estimating Magnitude and Frequency of Floods in the Southwestern United States*. Representative hydrologic results are shown in Table 2. The 100-year hydrologic results are shown graphically in Figure 2.

Hydraulic modeling was performed using the HEC-2, *Water Surface Profiles*, computer program using the geometry and frictional loss values from the field surveys. Regressions were performed to obtain various hydraulic variables in terms of discharges.

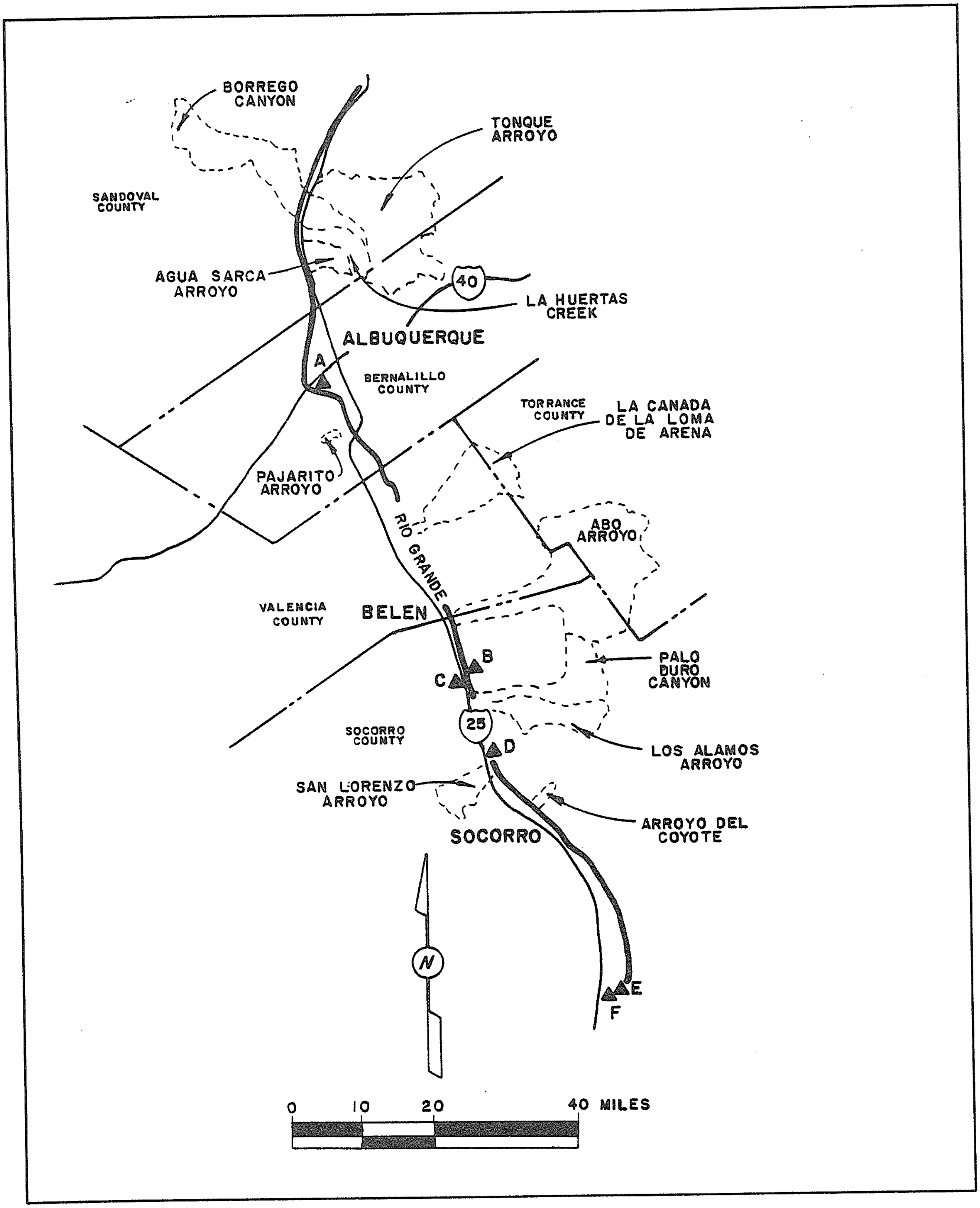

Figure 1. Study area.

TABLE 2. REPRESENTATIVE HYDROLOGIC RESULTS

Basin	Drainage Area (sq mi)	Peak Discharge (cfs) 2-yr	10-yr	100-yr	Runoff Volume (a-f) 2-yr	10-yr	100-yr
Agua Sarca	5.68	696	1,800	3,538	67	198	392
Palo Duro	63.50	86	4,655	11,849	23	885	2,439
Abo	290.00	0	9,534	28,091	0	2,663	7,954
Coyote	1.55	130	570	1,840	10	42	146
Comanche	15.00	370	1,560	5,660	81	345	1,266
Los Alamos	58.80	690	3,080	11,640	258	785	2,786
Las Huertas	29.20	490	2,110	8,260	83	359	1,441
San Lorenzo	30.50	480	2,380	8,610	117	538	1,919
Tonque	163.00	940	3,960	16,170	307	1,227	4,940
Borrego	75.00	800	3,360	12,810	296	1,183	4,482
Pajarito	0.85	80	430	1,450	3	18	78

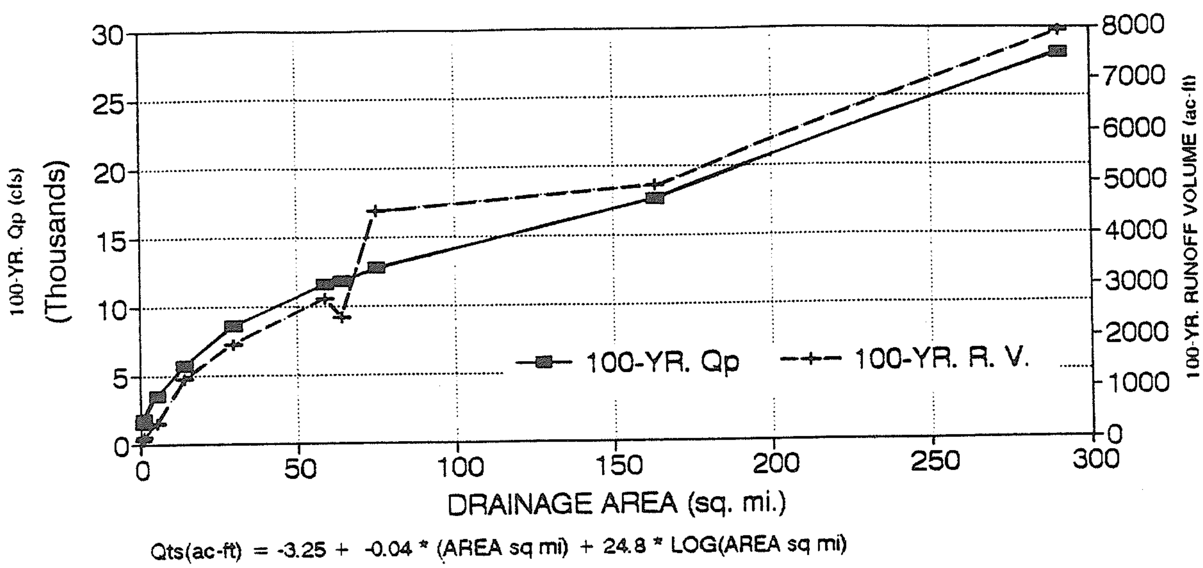

Figure 2. 100-year hydrologic results (*HEC-1 model results calibrated to USGS).

Watershed sediment yield computations were performed using the Modified Universal Soil Loss Equation (MUSLE). These values were used for the wash load component of the total sediment load and for calculating the Colby correction factor, which was applied to the bed material component.

The Zeller-Fullerton Equation (ZF) was used for the majority of bed material load, while the Meyer-Peter, Muller Equation (MPM) was used for large sized material (the upper portion of gradation curve).

The Zeller-Fullerton equation is:

$$q_s = 0.0064 \frac{n^{1.77} v^{4.32} G^{0.45}}{y^{0.3} D_{50}^{0.61}}$$

where q_s = bed load per unit width of channel (cfs/ft)

n = Manning's roughness
v = velocity (ft/s)
G = gradation coefficient = ½(D_{84}/D_{50} D_{50}/D_{16})
D_{84} = 84% finer sediment diameter
D_{50} = median sediment diameter
D_{16} = 16% finer sediment diameter
y = hydraulic depth (ft)

The Meyer-Peter, Muller equation is:

$$q_{bi} = \frac{12.85}{\sqrt{\rho \gamma_s}} (\tau_o - \tau_c)^{1.5}$$

where q_{bi} = bed load per unit width of channel (cfs/ft)

ρ = density of fluid (slugs/ft^3)
γ_s = unit weight of sediment (lb/ft^3)
o_o = bed shear stress (lb/ft^3)
o_c = critical shear stress for the particle size being considered (lb/ft^3)

Each of these equations were integrated over the various frequency runoff hydrographs to yield sediment volumes. These volumes were then scaled to their portion of the original gradation curve and the Colby correction factor was applied.

The wash load (from the MUSLE) volume and two bed material load volumes were combined to produce total sediment volumes for the various storms for each of the eleven selected sub-basins.

A regression analysis was then performed on the resulting sub-basin sediment volumes. The original plan was to produce three regression equations to reflect the three sub-basin categories. However, the analysis showed there was no substantial difference among the three classes so they were combined.

The Las Huertas Creek sediment volumes were extremely large relative to the other ten basins—it was clearly behaving differently from the others—and consequently, it was excluded from the regression analysis.

Total sediment volume equations were subsequently developed for the 2-, 5-, 10-, 25-, 50-, and 100-year events, as well as one for average annual conditions, as a function of drainage area. The non-linear correlation coefficients for the equations range from 0.77 to 0.86. The resulting regression equations are shown in Table 3. The 100-year and average annual fitted curves are shown graphically in figures 3 and 4, respectively.

COMPARISON OF RIO GRANDE CROSS SECTION DATA

Rio Grande mapping from 1972 and 1992 was obtained from the Bureau of Reclamation. Cross sections along fixed rangelines were developed for both mapping data sets. The differences between adjacent cross sections were used to compute changes in volume along the river bed between cross sections. The computed change in sediment volume over time was used to determine the locations of aggradation and degradation.

The volume change in acre-feet between two adjacent range lines was calculated and is presented graphically in Figure 5. The cumulative volume change in acre-feet from upstream to downstream is presented in Figure 6. The cumulative volume change as a result of river aggradation (positive) or degradation (negative) between Cochiti Dam and each gage is presented in Table 4.

TABLE 3. SEDIMENT VOLUME REGRESSION EQUATIONS

Return Period (yr)	Regression Coefficients* A_1	A_2	A_3	Standard Error of Estimate	Nonlinear Correlation
2	0.202	0.0469	5.91	5	0.78
5	-2.860	0.0723	26.90	16	0.81
10	-3.810	0.0386	45.60	22	0.86
25	-7.690	0.1770	83.20	47	0.86
50	-14.900	0.1790	139.00	85	0.82
100	-43.800	0.2200	280.00	166	0.77
Average Annual	-3.250	-0.0400	24.80	12	0.80

$Q_{ts} = A_1 + A_2$(Area) + A_3*log(Area)
where Q_{ts} = total sediment volume (a-f)
Area = drainage area (mi^2)

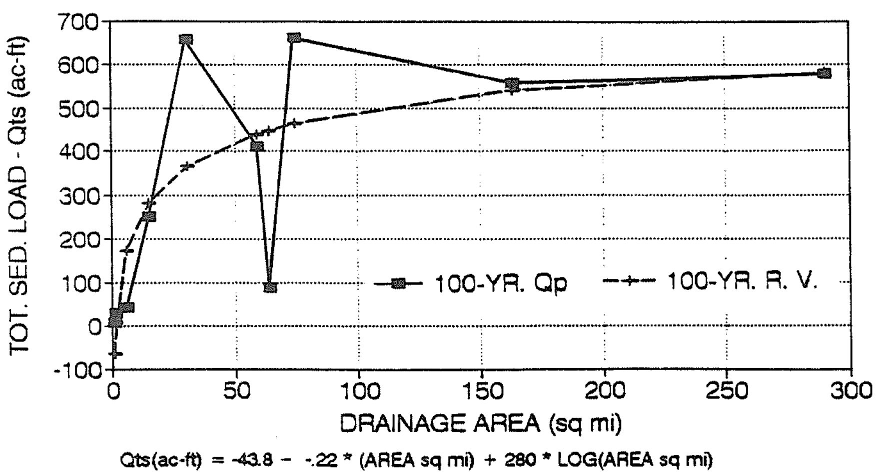

Figure 3. 100-year sediment load (10 tributary basins to the Rio Grande).

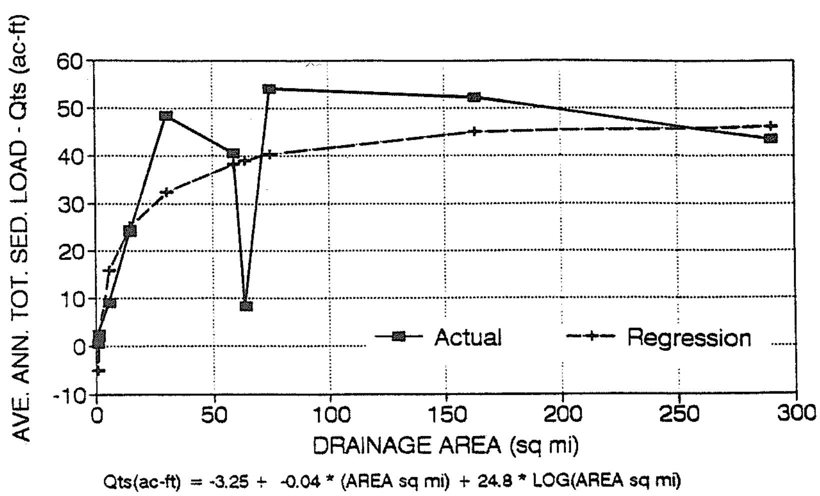

Figure 4. Average annual total sediment load (10 tributary basins to the Rio Grande).

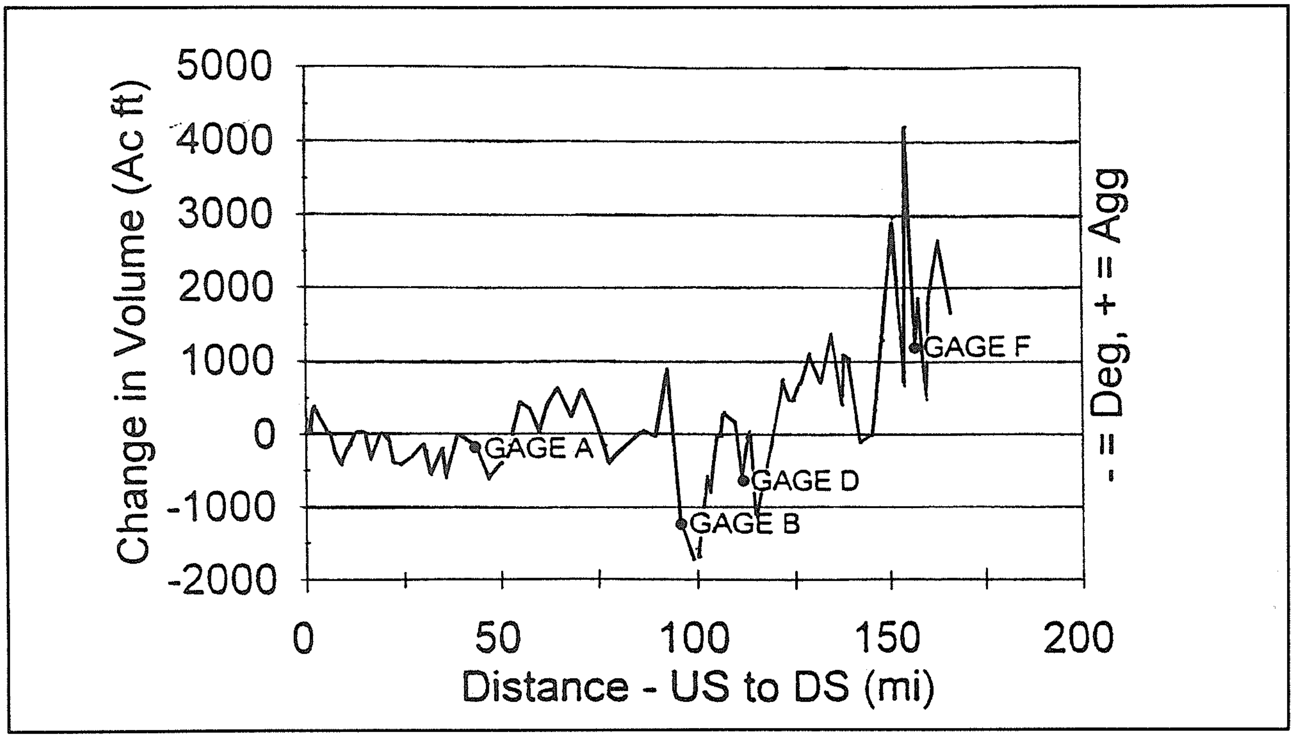

Figure 5. Change in sediment volume between rangelines (Rio Grande from Elephant Butte to Cochiti Dam).

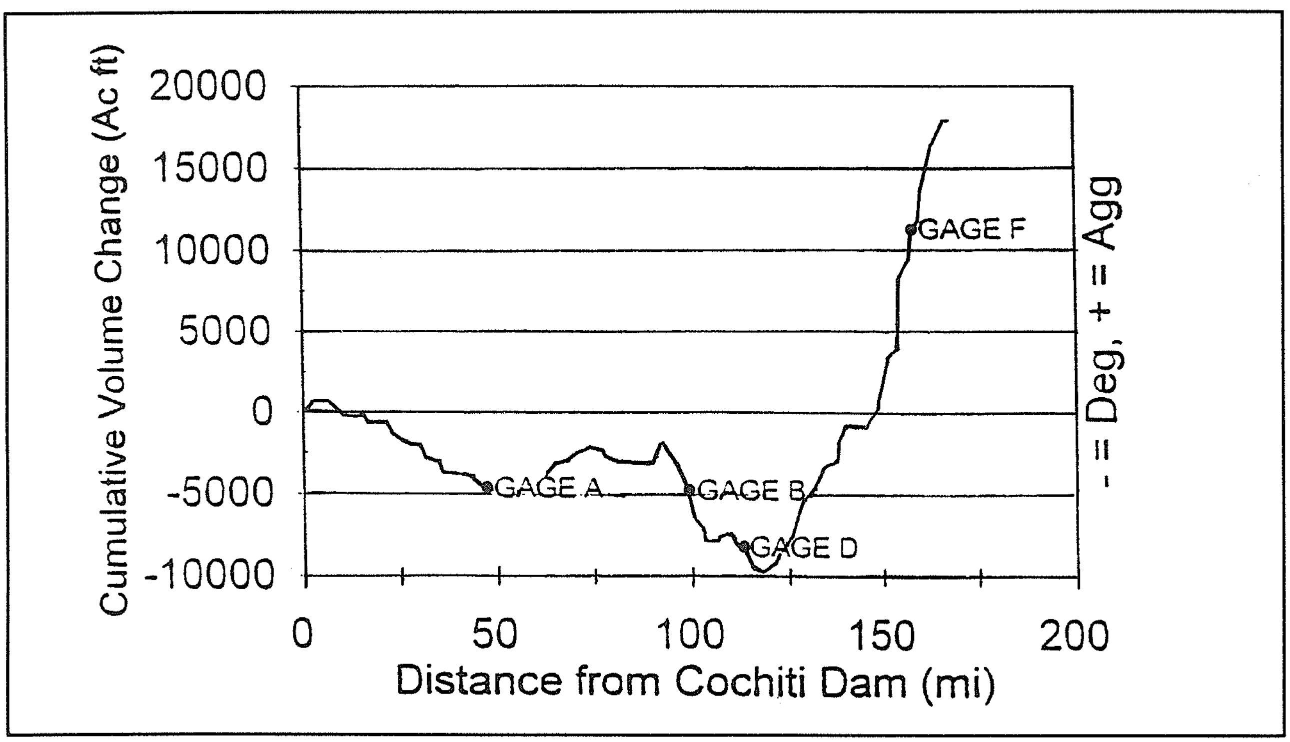

Figure 6. Cumulative change in sediment volume (Rio Grande from Elephant Butte to Cochiti).

TABLE 4. CUMULATIVE AND AVERAGE ANNUAL VOLUME CHANGE (Q_{sr}) AS CALCULATED FROM RANGELINES FROM COCHITI TO EACH GAGE

Reach	Cumulative Volume Change 1972-1992 (a-f)	Average Annual Volume Change 1972-1992 Q_{sr} (a-f/yr)
Cochiti to A	-4,671	-234
Cochiti to B	-4,782	-239
Cochiti to D	-8,245	-412
Cochiti to F	11,324	566
Cochiti to E. Butte	17,941	897

The Rio Grande was divided into four reaches and the cumulative volume change as a result of river aggradation (positive) or degradation (negative) for each reach is presented in Table 5 below:

TABLE 5. CUMULATIVE AND AVERAGE ANNUAL VOLUME CHANGE (Q_{sr}) AS CALCULATED FROM RANGELINES FOR EACH REACH (BETWEEN GAGES)

Reach	Cumulative Volume Change 1972-1992(a-f)	Average Annual Volume Change 1972-1992 Q_{sr} (a-f/yr)
Cochiti to A	-4,671	-234
Gage A to B	-111	-6
Gage B to D	-3,463	-173
Gage D to F	19,569	978

COMPARISON OF ELEPHANT BUTTE CROSS SECTION DATA

The Elephant Butte Reservoir resurveys were used to evaluate the reliability of the computed sediment data. Based on 73 years of record (1916-1988), the average annual volume loss rate is 7,800 acre-feet per year (a-f/yr); however, the most recent resurveys, which cover an eight-year period (1980-1988), show a current storage loss rate of 5,590 a-f/yr which presumably reflects the result of upstream dam construction, including Cochiti and Abiquiu reservoirs.

ANALYSIS OF SEDIMENT GAGE DISCHARGE DATA

The USGS collects sediment data at several locations and six of these locations, which were in the study area (Middle Rio Grande), were analyzed, as listed below. Figure 1 also shows the approximate locations of the sampling sites, one of which is located on the Rio Puerco just above its confluence with the Rio Grande. Another site is located on the low flow conveyance channel near San Marcial; the remaining four sites are either on the main stem or on the floodway where most of the flow (and sediment) would be transported.

Gage Designation	Gage Number	Gage Name
A	08330000	Rio Grande at Albuquerque
B	08332010	Rio Grande Floodway near Bernardo
C	08353000	Rio Puerco near Bernardo
D	08354900	Rio Grande Floodway at San Acacia
E	08358300	Rio Grande Conveyance Channel at San Marcial
F	08358400	Rio Grande Floodway at San Marcial

The construction of Cochiti Dam in 1976 on the main stem of the Rio Grande affected the sediment transport capacity of the river below the dam. Pre-1976 data are not compatible to those after the dam; and consequently, the 1976-1992 period of record was selected for the six gages used in this analysis.

The analysis was conducted on the flow rates and sediment volumes for both monthly and seasonal bases. Figure 7 shows the mean daily flow and suspended sediment values for each month of the year at the four Rio Grande main stem stations. At both the Albuquerque and Bernardo stations, the suspended sediment concentrations remain relatively uniform throughout the year. However, the Rio Puerco delivers a high concentrated sediment load in August (Figure 7). This results in correspondingly higher sediment concentrations in August and September in the Rio Grande at San Acacia and at San Marcial even when the flow rates are dropping (Figure 7).

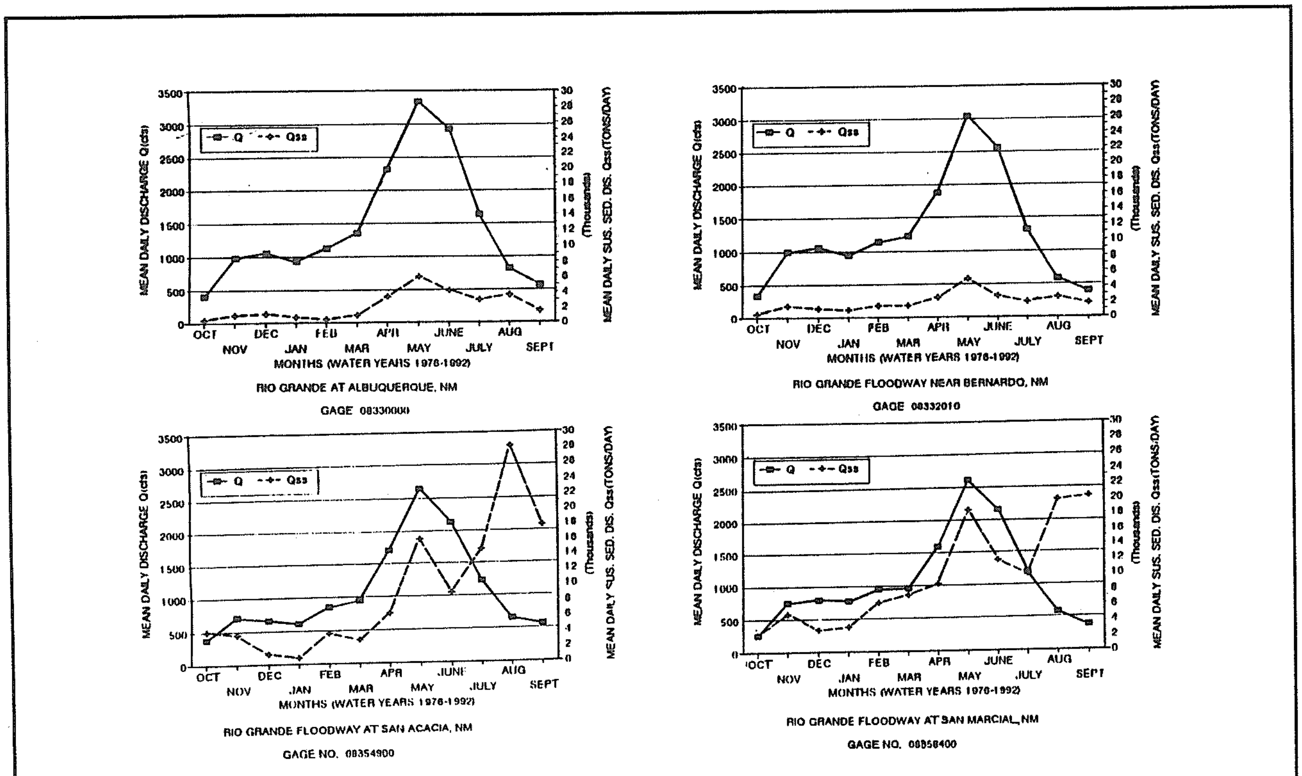

Figure 7. Mean daily discharge and mean daily suspended sediment discharge vs. month.

The USGS measures and publishes only the daily suspended sediment and water discharges at their gage locations; whereas the total sediment discharges were required for purposes of this study. The USGS occasionally has computed the daily total sediment discharge using the daily suspended sediment discharge. Initially this computation was performed using the Modified Einstein Equation to compute the bed material load, which was then added to the suspended load to determine total sediment load. After 30 years of accumulating such computed data, a double mass regression analysis was developed and the resulting equation is now used by the USGS to compute total load as a function of the suspended load.

By correlating the suspended and corresponding total sediment load data provided by the USGS, the applicable regression equation was derived and applied to all the other suspended sediment load data to determine the corresponding total sediment load. As expected, the correlations were very good with correlation coefficients ranging from 0.96 to 0.99.

The mean daily total sediment loads were then correlated to the mean daily flows at each of the USGS gages. The data suggest that some data may be outliers which were then eliminated from the regressions. The results are presented in Figure 8. In this case the correlation coefficients range from 0.60 to 0.89.

The developed total sediment-to-flow correlation equations for the gages are not valid for the 10% greatest flows as they predict total sediment loads less than the suspended load. To compensate for this, the maximum historical suspended sediment, as measured by the USGS at each gage, was used to establish the endpoints of the curves (at 0.1% of time equaled or exceeded) and the total sediment was assumed to be 1.15 times this maximum suspended sediment discharge. The total sediment discharge for the 5% and 10% exceedance points were then derived graphically. The total annual sediment load was then computed as the area under the curve.

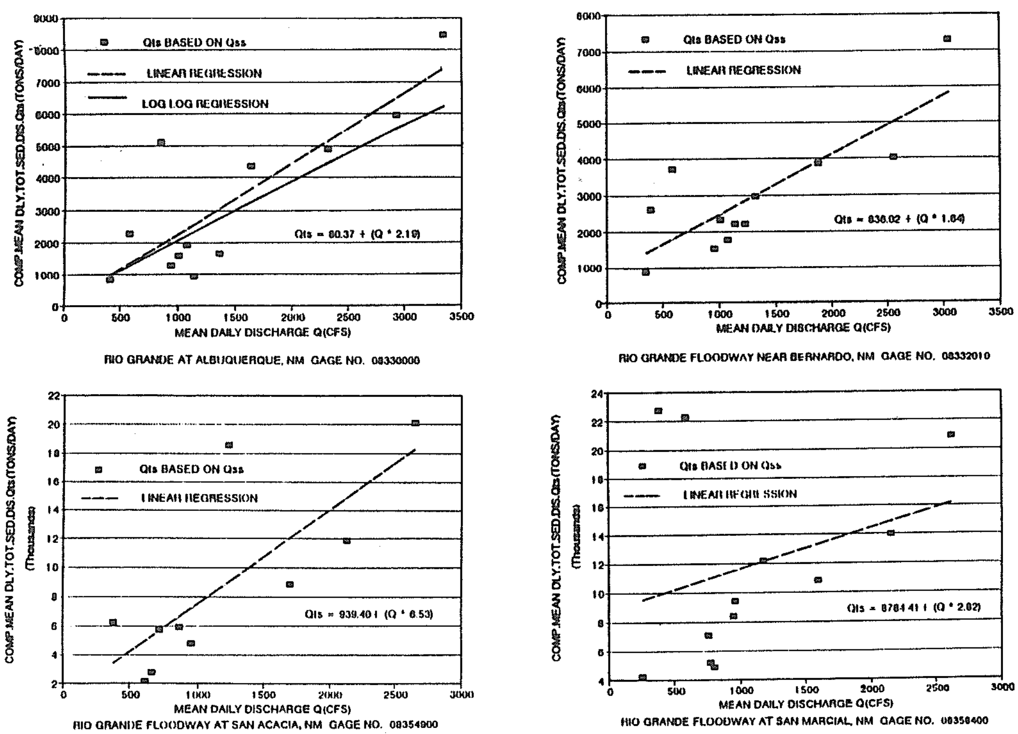

Figure 8. Computed mean daily total sediment discharge vs. mean daily discharge.

COMPARISON OF SEDIMENT VOLUMES

Cochiti to Each Gage

A volume balance computation was performed at each gage location. For each gage, Table 6 shows the computed sediment discharge of the upstream tributaries (Q_{st}), the cumulative change in river sediment upstream of the gage as a result of river aggradation/degradation as measured by rangelines (Q_{sr}) and the calculated sediment discharge at each gage (Computed $Q_{s\ gage}$). The sediment discharge at each gage ($Q_{s\ gage}$) is provided for comparison.

The calculated sediment discharge at each gage (Computed $Q_{s\ gage}$) was calculated as follows:

$$\text{Computed } Q_{s\ gage} = Q_{st} - Q_{sr}$$

TABLE 6. VOLUME BALANCE USING GAGE DATA, RIVER AGGRAD/DEGRAD DATA AND COMPUTED ARROYO SEDIMENT DISCHARGE (Gage data converted to acre-feet using 165 lbs/ft^3 unit weight)

	Q_{st} Sediment Volume from U.S. Tributaries (a-f/yr)	Q_{sr} Sediment Volume from River Aggrad/ Degrad (a-f/yr)	Computed $Q_{s\ gage}$ Sediment Volume Passing Gage (a-f/yr)	$Q_{s\ gage}$ Sediment Volume Passing Gage (a-f/yr)
Gage A	968	-234	1,202	1,125
Gage B	2,093	-239	2,332	1,345
Gage D	4,952	-412	5,364	6,012
Gage F	6,082	566	5,516	4,403

Reach by Reach Volume Analysis

A volume balance computation was performed for each reach between gage locations and is presented in Table 7. The computed aggradation/degradation by reach (Computed $Q_{sr\ gage\ 1\text{-}2}$) is calculated as follows:

$$\text{Computed } Q_{sr\ gage\ 1\text{-}2} = Q_{s\ gage\ 1} + Q_{st\ gage\ 1\text{-}2} - Q_{s\ gage\ 2}$$

Where, $Q_{s\ gage\ 1}$ is the sediment discharge at Gage 1, $Q_{st\ gage\ 1\text{-}2}$ is the computed sediment production of all tributary arroyos between Gage 1 and Gage 2, Actual $Q_{s\ gage\ 2}$ is the sediment discharge at Gage 2; Gage 1 represents the upstream gage and Gage 2 represents the downstream gage.

The aggradation/degradation of the Rio Grande as measured by rangelines is provided for comparison ($Q_{sr\ gage\ 1\text{-}2}$).

COMPARISON OF SEDIMENT LOAD DATA

Albuquerque Gage (Gage A): The Albuquerque Gage analysis yields a sediment transport rate of 1,125 a-f/yr as compared to the tributary inflow and river sediment production rate of 1,202 a-f/yr. These rates show excellent agreement.

Bernardo Gage (Gage B): The Bernardo Gage analysis yields a sediment transport rate of 1,345 a-f/yr as compared to the tributary inflow and river sediment production rate of 2,332 a-f/yr. These rates are relatively comparable because there are so many variables affecting the sediment transport that more exact comparisons were not feasible.

San Acacia Gage (Gage D): The San Acacia Gage analysis yields a sediment transport rate of 6,012 a-f/yr as compared to the tributary inflow and river sediment production rate of 5,364 a-f/yr. These rates show excellent agreement. It should be noted that (1) the Low Flow Conveyance Channel diverted water upstream of this gage during part of the period of analysis (which may have affected the gage sediment flow predictions), and (2) the Socorro Main Canal (irrigation canal) diverts water upstream of this gage.

San Marcial Gage (Gage F): The San Marcial Gage analysis yields a sediment transport rate of 4,403 a-f/yr as compared to the tributary inflow and river sediment production rate of 5,516 a-f/yr. The Elephant Butte Reservoir resurveys were used to evaluate the reliability of the computed sediment data. The most recent resurveys, which cover an eight-year period (1980-1988), show a current storage loss rate of 5,590 a-f/yr.

TABLE 7. VOLUME BALANCE USING GAGE DATA AND COMPUTED ARROYO SEDIMENT DISCHARGE
(Gage data converted to acre-feet using 165 lbs/ft^3 unit weight)

	$Q_{s\ gage\ 1}$ (a-f/yr)	$Q_{st\ gage\ 1\text{-}2}$ (a-f/yr)	$Q_{s\ gage\ 2}$ (a-f/yr)	Computed $Q_{sr\ gage\ 1\text{-}2}$ (a-f/yr)	$Q_{sr\ gage\ 1\text{-}2}$ (a-f/yr)
Cochiti to Gage A	0	968	1,125	-157	-234
Gage A to Gage B	1,125	1,125	1,345	905	-6
Gage A to Gage D	1,125	3,984	6,012	-903	-179
Gage A to Gage F	1,125	5,114	4,403	-1,836	799
Gage B to Gage D	1,345	2,859	6,012	-1,808	-173
Gage B to Gage F	1,345	3,989	4,403	-931	805
Gage D to Gage F	6,012	1,130	4,403	2,739	978

CONCLUSION

The comparison of sediment discharge rates at each gage location using various sediment data computational procedures indicates relatively comparable sediment discharge rates. The reach by reach comparisons are less encouraging. However, as the reach length increases, the correlation generally improves as seen in Table 7. Some of the variables affecting these sediment transport rates are listed below.

- The unit weights of the river bed material are variable. The unit weight of in-place material removed from the river bed is probably greater than that of the material deposited in the river. Measuring the in-situ unit weights at various locations was not feasible; therefore, no unit weight based adjustments were made to the measured volumes.
- The period of study for the river cross sections was 1972 to 1992. This period includes pre and post Cochiti Dam data. The recent average annual cumulative volume change for the river (post Cochiti) may be different than that for the longer term.
- The sediment flow was calculated as a function of tributary and river flow. No adjustments were made for the diversion of flow (and sediment) into irrigation systems.
- Several arroyos do not flow directly into the Rio Grande. The computed sediment production of the tributary arroyo does not exclude the sediment produced in these arroyos. This sediment may not enter the Rio Grande or the sediment may enter riverside drains and enter the Rio Grande at the end of the riverside drain.
- The volume of sediment calculated from the gages is highly dependent on the high flow event. Approximately 80 percent of the sediment load passes the gage during the 5 percent highest flows and approximately 85 percent of the sediment load passes the gage during the 10 percent highest flows. Since insufficient data exist to calculate the total sediment load from the measured suspended sediment loads in these events, approximate methods were used.
- Four sets of data were used, but the time reference for each data set is different. The tributary arroyo sediment discharges were computed as a function of flow, but the flows were calibrated to long-term regional weather data. The river bed aggradation and degradation computations were based on 1972 to 1992 mapping. Computations of the average annual volume loss in Elephant Butte Reservoir were based on mapping from an eight-year period (1980-1988). The sediment flow at the gages was based on the 1976-1992 period of record for the six gages used in this analysis.