A geological perspective of sediment storage and delivery along the Rio Puerco, central New Mexico

David W. Love
New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

ABSTRACT

During the geologic evolution of the Rio Puerco drainage basin, sediments eroded from the headwaters have been delivered downstream at episodically contrasting rates and have been stored in a hierarchy of different geomorphic features. Initially, all sediments were delivered to a tectonically-subsiding closed basin. As the tectonic basin filled and became integrated as part of the Rio Grande drainage, the Rio Puerco stored a large volume of sediment in a broad alluvial plain graded to the Rio Grande. Although the channels were probably more efficient at delivering sediment to the Rio Grande than at present, overall efficiency of the system was reduced because of interchannel sediment storage. As the Rio Puerco eroded its valley during the past several hundred thousand years, sediment delivery was episodically much more efficient; not only was more sediment removed from the system than previously, larger clasts were also transported. At present the Rio Puerco drainage system is extremely inefficient in sediment delivery. Sediment is stored locally throughout the system in fans, valley fills, and even in the active channel. While tectonic deformation plays a role in sediment storage in the long term, over shorter time intervals the amount of water for sediment transport determines sediment delivery, the amount in storage, and the geomorphic features where sediments are stored.

INTRODUCTION

The Rio Puerco integrates a large (18,892 km^2) drainage basin in a predominantly semiarid area straddling three physiographic provinces in an active tectonic setting. The drainage evolved geologically over at least the past 30 Ma (million years). The Rio Puerco illustrates the problems of temporal and spatial scales in estimating basin sediment yield and the variety of processes conveying sediments and geomorphic features storing sediments. Evidence for storage of fluvial sediment and recycling of previously stored sediments on several temporal and spatial scales is preserved along the lower reaches of the drainage and at least locally in remnant deposits upstream to the headwaters. Over the long term, all of Schumm and Lichty's (1965) classic variables have influenced sediment movement and storage in the drainage basin. Non-fluvial deposits play an important role in sediment storage. Within the drainage system, amounts of fluvial-sediment storage depend primarily on climatic and tectonic factors. The Rio Grande, the larger base-level stream at the mouth of the Rio Puerco, is affected by the same factors. Groundwater interacts with the Rio Grande, but is generally below the gradient of the Rio Puerco. Recently (geologically speaking), sediment storage and delivery have depended not only on natural processes, but also on human history and land use.

The purpose of this paper is to present an overview of sediment storage and delivery in the Rio Puerco drainage from a geological perspective. Most of the interpretations are based on the geometry and facies of stored sediment left along the margins of the stream. These deposits show that sediment storage and delivery operate on several spatial and temporal magnitudes. The references provide entry to an extensive literature on the Rio Puerco.

Methods

The drainage basin was studied in terms of volumes of erosional and depositional landforms and analysis of internal sedimentary facies within Rio Puerco deposits. Volumes of sediments in storage or removed by erosion were calculated after estimating the three-dimensional geometry of the geomorphic-sedimentological feature containing the sediment. The estimates are considered rough, first-order approximations subject to revision. Yet their order of magnitude gives an indication of their importance in terms of their geologic contibution to sediment storage or delivery in the past and in the future. Sedimentary facies within the deposits are used to interpret the mode of deposition while the size and composition of clasts indicate general sources for the sediment.

GEOMORPHOLOGY OF THE DRAINAGE BASIN

The Rio Puerco drains an area along the physiographic boundaries between the Colorado Plateau, the Southern Rocky Mountains (Nacimiento Mountains), and the Basin and Range (Albuquerque basin along the Rio Grande, Fig. 1). The shape of the drainage basin reflects the lithology, tectonics, and the maturity of development of the headwater areas. The curvilinear northwestern margin reflects the mature competition between the Rio Puerco and the drainages to the west developed in similar sandstones and shales. The north-south alignment of the eastern margin reflects the north-south tectonic alignment and drainage divide of the Nacimiento Mountains and north-south young faults in the Albuquerque basin (Fig. 2).

The Rio Puerco has captured headwater drainages in the northern Nacimiento Mountains, but tributary drainages in the southern Nacimientos have been captured by the next drainage to the east. The cookie-cutter pattern of the southern edge of the Rio Puerco drainage reflects the relatively recent development of the Rio Salado to the south in response to tectonic developments and igneous intrusions along the southern margin of the Colorado Plateau.

The Rio Puerco drainage may be divided into several subbasins and areas with little surface drainage. The upper Rio Puerco encompasses about 1000 km^2 of high topographic relief and diverse lithology (Fig. 1, 2). The middle and lower Rio Puerco

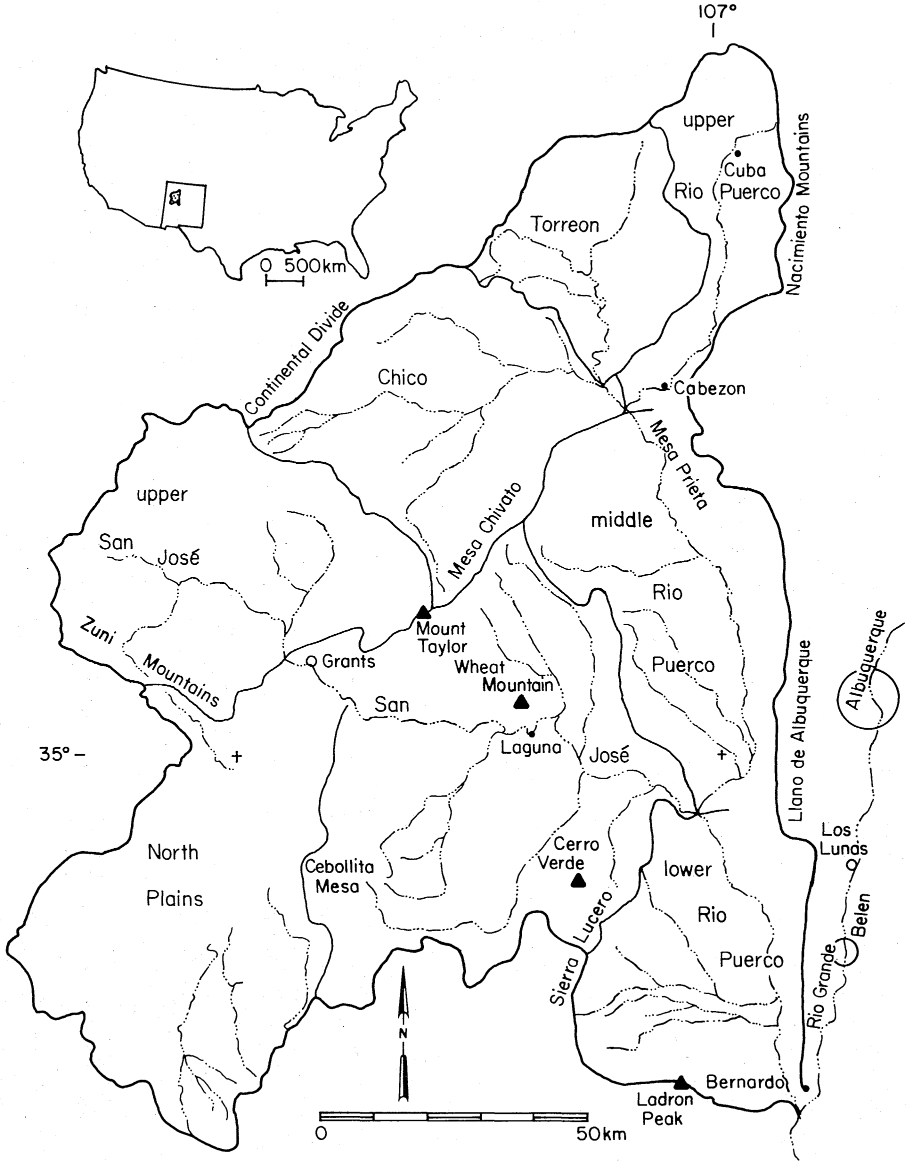


FIG. 1. Rio Puerco drainage basin, subbasins, major towns, and major landforms.

subbasins have wider valleys, valley margins of lower topographic relief, and are bounded on the east by the Llano de Albuquerque and on the west by several large mesas (Fig. 3). The Chico and Torreon drainages encompass an area of 3440 km^2 and drain the mesas, questas, and valleys of Cretaceous and lower Tertiary sandstones and shales. The Rio San Jose drainage (the major tributary parallelling $35^{O}N$, not Arroyo San Jose, north of Cuba;

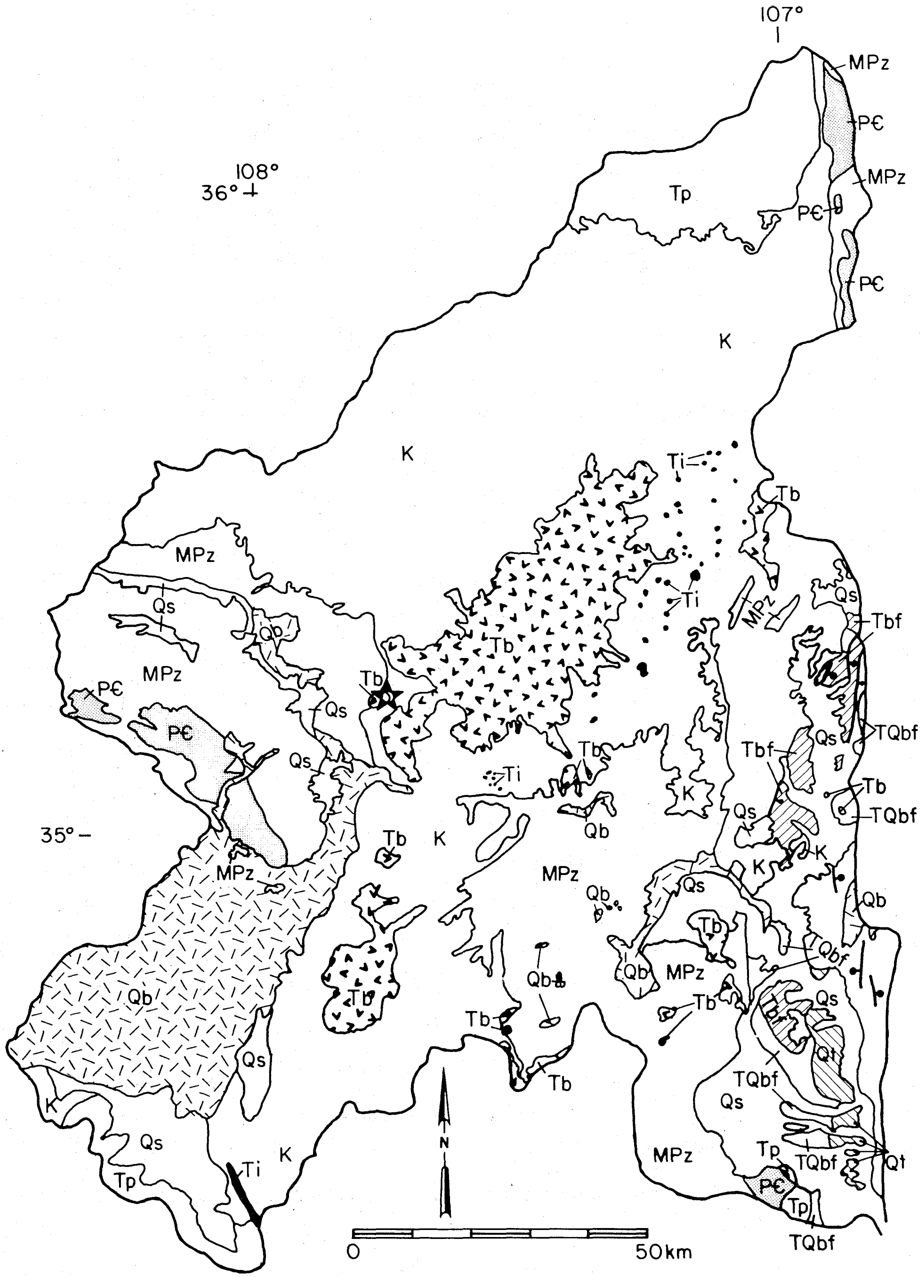


FIG. 2. Generalized geologic map of the Rio Puerco drainage basin. Symbols for rocks from oldest to youngest: PЄ (gray stipple) = Precambrian metamorphic and igneous rocks; MPz = Paleozoic and lower Mesozoic sediments (mostly redbeds and limestone); K = Cretaceous sandstones and shales; Tp = Tertiary Paleogene sandstones and shales; Tbf = Tertiary (Miocene) basin

Fig 3) drains 9700 km^2 of high topographic relief and diverse lithology.

Large areas (3285 km^2) covered with basalt flows (North Plains, Mesa Chivato; Figs. 1 and 2) contribute little surface runoff, although springs exist at the lowest margins of the flows. The basalt flows also resist erosion and preserve previous topographic levels. These levels influence the margins of the Rio Puerco and Rio San Jose valleys (Fig. 3).

The stream valleys of the Rio Puerco drainage consist of sloping valley margins cut in bedrock or semiconsolidated basin fill, stream terraces, the valley floor, underlain by thick alluvial deposits, and the incised axial stream channel (arroyo) with related features. The valley margins generally consist of alluvial fans between ridges of more resistant older deposits. Terraces commonly parallel the valley along the margins, but are discontinuous. Terraces along tributaries may show inverted topography where previous stream valleys are now protected by gravel caps. The valley floors are relatively flat, consisting of sediment layers built up by flooding from the axial stream when it was not entrenched, and by deposition from the toes of alluvial fans along the valley margins. Valley floors presently are undergoing erosion by lateral and vertical cutting of surface streams and underground soil pipes (Fig. 4).

The modern Rio Puerco has developed distinctive geomorphic features within the confined arroyo walls. Along the middle and lower Rio Puerco, the arroyo ranges from 145-245 m wide between walls 8-13 m high. Geomorphic features within and adjacent to the arroyo include an inner channel, inner floodplain, and terraces (Fig 4). The upper Rio Puerco and tributaries locally show similar features, but they also locally have braided arroyo bottoms. The Rio Puerco near Bernardo is less incised and joins the Rio Grande in a normal tributary junction.

Eolian deposits are common in most parts of the drainage basin, but generally they are thin and only dominate the landscape in a few well defined upslope areas. Nonetheless, they are locally important in reducing runoff and in storing loose sediment that otherwise would be mobilized by water.

Vegetation becomes more sparse at lower elevations, but riparian woody species (Tamarisk, willows, cottonwood) dominate the channel margins along the mainstem Rio Puerco and most tributaries. Native bunch-grass cover along valley margins and in tributaries depends on soils, previous precipitation, and on grazing.

Figure 2. Caption continued

fill of Albuquerque basin; Tb (random v pattern) = Tertiary basalts; Ti (black) = Tertiary intrusives; star = vent of Tertiary obsidian; TQbf = (diagonal left cross-hatch) = Tertiary and Quaternary basin fill; Qb (random dash pattern) = Quaternary basalt; Qt (diagonal right) = Quaternary terraces; and Qs = Quaternary sediments (mostly alluvium; shown only where width >1.5 km). Prominent young faults are heavy lines with ball and bar on downthrown side. Map modified from Clemons et al (1982).

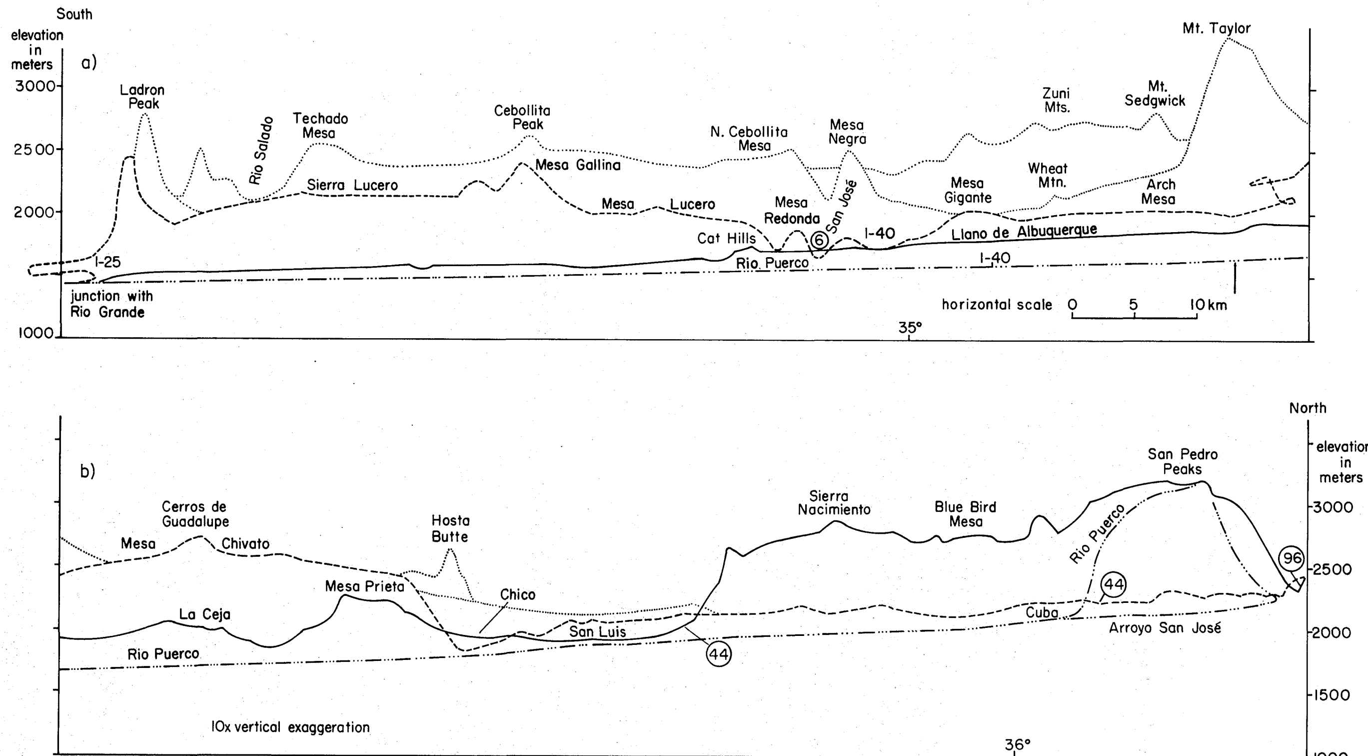


FIG. 3. Longitudinal profiles of the Rio Puerco (dash-three dot line), east edge of drainage basin (solid line), west edge of Puerco valley (dashed line, see Fig. 1 for location), and prominent mesas and mountains west of Rio Puerco valley (dotted lines) projected onto north-south line at 107°W. Vertical line beneath Rio Puerco at latitude of Mount Taylor marks beginning of thick fill of Albuquerque basin.

Present Water and Sediment Budget

Except for reaches below springs and tributaries with discharge from dewatering of uranium mines, the Rio Puerco is an ephemeral stream, flowing only in response to precipitation and snowmelt. Seasonal, annual and areal variations are extreme. Precipitation in the mountainous headwaters ranges up to at least 650 mm per year. Annual precipitation at Grants and Cuba averages 216 and 349 mm respectively, while at Bernardo the average is 191 mm (Gabin and Lesperance, 1977).

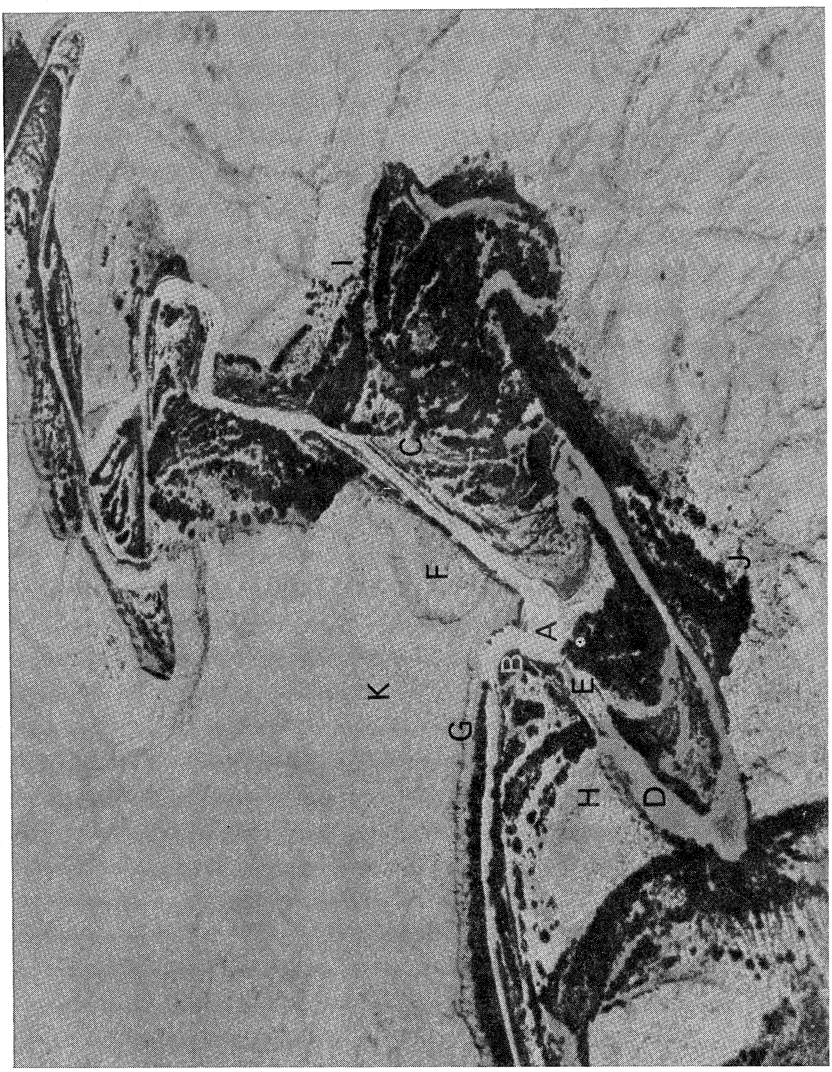
Water discharge in the Rio Puerco depends on the season and location within the basin. Discharge along the Rio Puerco is generally flashy. In dry years, no flow may occur for months; in wet years, low flow may continue for months. In general, flow occurs at Bernardo, at the distal end of the drainage basin, only 30% of the time. Flow in the headwaters typically is bimodal, one peak on the order of 80,000 m^3 per day occurring in May from spring snowmelt, and a second peak on the order of 66,000 m^3 per day occurring in August during the summer thunderstorm season. Summer runoff is more flashy and can produce larger floods than spring flows. The lower Rio Puerco has less seasonal bimodality and is dominated by summer floods. Floods tend to be less peaked and of longer duration downstream.

The Rio Puerco is a "losing" (influent) stream, particularly along the lower reaches. According to Heath (1983), an average of 30,000 m^3/km is lost to evaporation and to the channel bed each year. Along the lower Rio Puerco up to 0.15 m^3/sec is lost during the winter and up to 0.30 m^3/sec is lost during the summer (Heath, 1983).

The Rio Puerco is infamous for its high suspended-sediment loads. Nordin (1963) reported suspended-sediment loads in the range of 327,000 to 418,000 ppm near Bernardo and Bondurant (1951) reported 680,000 ppm which was 75% sand. Suspended-sediment discharge is estimated to average 2.7 million metric tons per year (Amin, 1983). Bedload discharge has not been measured consistently enough to provide an annual estimate, but the U.S. Bureau of Land Management (1972) estimated that the Rio Puerco contributes 6 percent of the water and over 50 percent of the sediment in the Rio Grande downstream from Bernardo to Elephant Butte Reservoir.

Sources of Sediment

Several areas of distinct lithologies exist within the Rio Puerco drainage (Fig. 2). The vast majority of sediment is derived from the drab brown and gray upper Mesozoic (predominantly Cretaceous) rocks of the northwest and west-central part of the drainage basin (Fig. 2). Their subdued colors and clasts of fossil pelecypods and petrified wood are indicative of these source rocks. Red-colored sand and clay and limestone clasts are derived from upper Paleozoic and lower-middle Mesozoic rocks along the Sierra Lucero and locally along the flanks of the Zuni and Nacimiento Mountains. Clasts of hard crystalline and metamorphic rocks are derived primarily from the Nacimiento and Zuni Mountains. Minor amounts of quartzites and other metamorphic rocks are recycled by erosion of lower Tertiary and lower Mesozoic sediments. Due to uplift and stream capture,


I
C
F
K
G
B
A
E
H
D
J

present sources of mid-Tertiary welded-tuff clasts are outside the drainage basin. Earlier sources of the tuff are buried within the lower part of the basin. Basaltic clasts may be derived from several areas, but obsidian is derived only from flows near Grants (Fig. 2).

Ages of rocks and sediments and brief history of drainage basin

Time control is based on radiometric dates from several volcanic rocks in the drainage basin and fossils included in some deposits (Table 1). Radiocarbon dates on charcoal from Holocene valley fill also provide time control on recent local episodes of erosion and sediment storage.

The early geologic history of the Rio Puerco-Rio San Jose system is not well known. The drainages probably developed as the Albuquerque structural basin began to subside approximately 27 Ma ago. The basin was a closed bolson with alluvial aprons around the margins and clay-rich playa deposits near the center (Wright, 1946; Kelley, 1977). It is possible that originally the present Albuquerque basin began as two separate basins which later coalesced. Early alluvial deposits in the basin, presently exposed along the western margins, indicate easterly and southerly transport directions into the basin from highlands to the west and north (Machette, 1978; Tedford, 1981). Eolian deposits were common.

The Albuquerque basin continued to subside and accumulate sediments until about 5 Ma, when the Rio Grande entered and traversed the eastern third of the basin. At that time, the Rio Puerco, Rio San Jose, and other western tributaries built a wide, low-relief alluvial plain across the basin to the south-flowing Rio Grande. Both the Rio Grande and western tributaries continued to aggrade within the Albuquerque basin until less than 1 Ma ago (Bachman and Machette, 1977; Machette, 1985). Their sediments buried volcanoes that erupted on the alluvial plain and buried soils which had accumulated on stable portions of the plain. The channels shifted back and forth across the basin as they aggraded, but the Rio Grande stayed in the eastern third of the basin. In the headwaters of the Rio Puerco and Rio San Jose, volcanic eruptions at different times covered parts of the landscape, preserving erosional levels. The Mount Taylor-Mesa Chivato volcanic field covered a major part of the upland landscape between 4.5 and 3 Ma (Grimm, 1985). Smaller eruptions such as those on Mesa Prieta, Wheat Mountain, and Cerro Verde have preserved intermediate levels of stream erosion since then (Table 1).

FIG. 4. Geomorphic features of the lower Rio Puerco arroyo and valley floor. Letters identify the inner channel (A), point bars along the channel (B), an inner floodplain (C), including oxbows (D), and sand plugs (E), strath and fill terraces above the inner floodplain (F), vertical arroyo walls (G), remnants of valley fill within arroyo (H), gently- to steeply-graded eroded slopes (I), mouths and alluvial fans of soil pipes and tributaries (J), and uneroded valley floor (K). Photograph by K. Novo-Gradac and A. Gutierrez, June, 1982 (from Popp et al, 1983).

Table 1.

AGE	LOCATION	METHOD	REFERENCE
AD 1325-1450	buried channel lower Rio Puerco	pottery	Eidenbach (1982)
AD 1100 (±200)	buried channel lower Rio Puerco	pottery	Eidenbach (1982)
150 BC (±105)	buried channel lower Rio Puerco	14C	Eidenbach (1982)
340 BC (±70)	0.7 m below surface of valley floor	14C	Eidenbach (1982)
350 BC (±150)	2.5 m below surface of valley floor	14C	Eidenbach (1982)
660 BC (±70)	70 m below surface of alluvial fan	14C	Eidenbach (1982)
0.14 Ma (±0.038)	youngest Cat Hills basalt flow	K-Ar on basalt	Kudo et a (1977)
0.19 Ma (±0.04)	Albuquerque volcanoes on terraces of Rio Grande	K-Ar on basalt K-Ar on basalt	Bachman e al (1975)
0.32 Ma (±0.2)	Cerro Verde-Suwanee flow	K-Ar on basalt	Bachman & Mehnert (1978)
0.38 Ma (±.25)	Laguna flow	K-Ar on basalt	Lipman & Mehnert (1980)
0.62 Ma	ash in fluvial deposits in remnant west of Rio Puerco	correlation to Lava Creek B ash from Yellowstone	Izett & Wilcox (1982)
1.1 Ma	ash overlying Cerro de Los Lunas	correlation to Tsankawi ash of Jemez Mountains	Bachman & Mehnert (1978); Izettet a (1981)
1.01 Ma (±0.10)	Cerro de Los Lunas	K-Ar on basalts	Bachman & Mehnert (1978)
1.12 Ma (±0.04)			
1.31 Ma (±0.05)			
1.1-1.3 Ma	Rio Grande valley	Cerro Toledo pumice and ash from Jemez	Izett et al (1981)
1.4 Ma	beneath Los Lunas volcano; correlative beneath basalt of Cat Mesa (?)	Guaje pumice and ash from Jemez	Izett et al (1981)
1.4-4.0 Ma	exposed fill in central Albuquerque Basin	Blancan-age fossil fauna	Tedford (1981)
2.2 Ma (±0.3)	Mesa Prieta	K-Ar on basalt	Armstrong et al (1976)
2.42 Ma (±0.18)	Wheat Mountain flow	K-Ar on basalt	Lipman & Mehnert (1980)

Table 1 (cont'd)

AGE	LOCATION	METHOD	REFERENCE
3.7 (±0.4)	Mesa Carrizo flow	K-Ar on basalt	Bachman & Mehnert (1978)
7.2 (±0.6)	Mesa Gallina flow	K-Ar on basalt	Bachman & Mehnert (1978)
7-9 Ma	Gabaldon badlands (mid-level basin fill)	early Hemphillian fossil fauna	Lozinsky & Tedford (1986)
21 Ma	Zia Sand (lower basin fill)	fossil fauna	Tedford (1981)
26.3 Ma (±1.1)	flow in basal basin fill	K-Ar on basaltic andesite	Machette (1978)

After 1 Ma, the Rio Grande incised the basin fill episodically, with at least three terrace levels marking some depositional intervals during valley incision (Lambert, 1978). The Rio Puerco-San Jose system incised as well (Wright, 1946). The north-south orientation of the Rio Puerco drainage appears to have been controlled in part by faults (Fig. 2). The Rio Puerco also developed terraces similar to those of the Rio Grande (Bryan and McCann, 1937; Wright, 1946; Love and Young, 1983).

At the end of the Pleistocene (roughly 15,000 years ago), the Rio Grande and Rio Puerco were incised at least 30 m deeper than their present levels (Hawley et al, 1976). Their floodplains and valley floor have aggraded episodically since then. The Rio Puerco has had numerous cycles of cut-and-fill of channels within the Holocene valley fill, but detailed chronology remains to be completed (Love and Young, 1983).

The Rio Puerco drainage has been used locally for agriculture for at least the past 2,000 years and grazing pressures have persisted since the Spanish arrived in 1540 (Eidenbach, 1982). Anglo dams and agricultural projects have failed to control the mainstem Rio Puerco, but have been successful at retarding erosion in small drainages (Lopez, 1982; Burkham, 1966).

SCALES OF EROSION

Erosion within the Rio Puerco drainage basin can be considered on progressively smaller spatial and temporal scales, beginning with the whole basin over millions of years to modern erosion of the channel floor during one flow event. Estimates of the amount of sediment removed from the entire drainage basin depend on the geometry of the drainage basin through time and the tectonic and depositional changes in the drainage. For example, as summarized above, the drainage debouched into the closed Albuquerque structural basin prior to about 5 Ma and then began to flow south with the Rio Grande shortly after 5 Ma. The amount removed from the headwaters and stored within the downwarped basin prior to 5 Ma can not be estimated until geometry of the basin floor is determined.

Table 2. Order-of-magnitude estimates of sediments eroded from o stored in various geomorphic-sedimentologic features of the Rio Puerco drainage basin.

Feature	Estimated volume in km^3
Erosional	
sediment removed from San Jose subbasin below 2440 m elevation	1300
sediment removed from Chico and upper Rio Puerco subbasin below 2440 m elevation	850
sediment removed from middle and lower Rio Puerco valley below maximum level of basin fill	200
sediment removed from present arroyo cut of Rio Puerco	0.12
Depositional	
upper basin fill (Llano de Albuquerque and remnants containing obsidian)	50
soil (pedogenic), local colluvium, and eolian deposits	10
alluvial fill of tributary valleys	9
alluvial aprons (constructional and relict)	7.2
alluvial fill of Rio Puerco valley	
upper	1.1
middle and lower	5.1
landslides, talus	1.4
large buried channels within alluvium of lower Rio Puerco valley	0.1
floodplain facies of middle and lower Rio Puerco	0.03
active bars within Rio Puerco channels	0.001[illegible]
average annual suspended sediment discharge to Rio Grande (if deposited at 1.6 g/cc density of sediment)	0.001[illegible]

About 850 km^3 have been eroded below the level of 2440 m elevation (approximate base elevation of the 3 Ma basaltic cap oi Mesa Chivato) in the Chico-Torreon-upper Rio Puerco subbasins anc about 1300 km^3 have been eroded from the Rio San Jose subbasin (Table 2).

Based on the extent of basin-fill deposits, at least 250 km^3 were removed from the headwaters between 3 Ma and 1 Ma ago and deposited in the Albuquerque basin. The present middle and lower Rio Puerco valley is incised through basin-fill deposits and approximately 200 km^3 have been removed in a series of erosional stages, alternating with episodes of aggradation. Erosion of the middle and lower Rio Puerco involves both vertical incision by the mainstem Rio Puerco and lateral backwearing of the valley margins by tributaries.

As summarized above, during the late Pleistocene and Holocene (perhaps past 15,000 years) the valley floor of the Rio Puerco has aggraded 30-40 m. Within this period of aggradation, however, are episodes where channels ranging from 2 to 7 m deep and 10 to 250 m wide have eroded and back-filled. The present erosional episode, much of which has occurred during the past 200 years, has removed about 0.12 km^3 of alluvium from the Rio Puerco valley (Bryan, 1928; Elliot, 1979). Most of that erosion has occurred episodically during major floods (Heath, 1983).

Between major floods, much of the inner channel and inner floodplain is reworked laterally and some valley fill is also removed (Wells et al, 1983).

TYPES OF SEDIMENT STORAGE

Sediments within the basin are stored in several categories at several scales of geomorphic-sedimentological features (Table 2). The largest feature where sediments are stored is the Llano de Albuquerque, the former maximum level of basin fill in the Albuquerque structural basin. Roughly 50 km^3 of sediment have been stored in the upper 30 m of this landform for at least the past 0.5 to 1 Ma (the upper 30 m contains clasts of 3-Ma obsidian, 1.1-1.4 Ma volcanic ashes, and 1.4-4 Ma fossils). As summarized above, prior to 1 Ma, the ancestral Rio Puerco and ancestral San Jose drainages delivered sediments to aggrade a large, low-relief alluvial plain across the entire middle and lower parts of the present Rio Puerco drainage, including the Llano de Albuquerque to the Rio Grande. These deposits are dominated by fluvial crossbedded coarse, pebbly sand, but they also contain fine-grained overbank facies, buried soils, and eolian components. None of the beds are laterally continuous for more than a few hundred m in transverse sections. Remnants of these deposits also occur west of the present Rio Puerco valley from Interstate 40 south to Bernardo. Erosion of these deposits recycles clasts into the present Rio Puerco valley.

The second most extensive class of deposits which store sediment for later recycling are eolian deposits, local colluvium, and soils (in a pedogenic sense) associated with stable upland surfaces (U.S. Army Corps of Engineers, 1973). Landslides and talus along the margins of the larger mesas and mountain terrain may be considered in this category as well. The availability of the sediments is dependent on geomorphic stability of it topographic setting, the amount of vegetation, and on precipitation-runoff relationships.

Alluvium in tributary valleys and along the axial Rio Puerco also constitute major reservoirs of stored sediment. Both the middle-lower reaches of tributaries and almost all of the Rio Puerco have aggraded episodically over at least the past 15,000 years. Alluvium in the valley of the lower Rio Puerco is at least 40 m thick (Heath, 1983). Aggraded sediment consists both of axial stream facies and alluvium/colluvium from valley

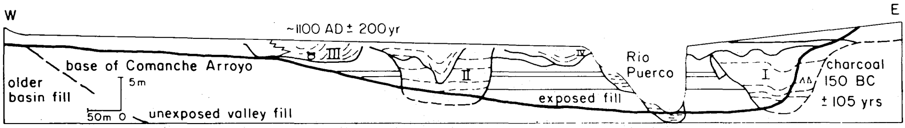


FIG. 5. Schematic cross section of upper valley-fill alluvium of lower Rio Puerco valley near 34°34'N, showing major buried channels (I and II) and minor buried channels (III and IV). Pottery dates channel III. Modified from Love and Young (1983) with NMGS permission.

margins. Small valleys may show no cycles of cut-and-fill within the aggradational sequence, but most large valley floors have one or more cycles of cut-and-fill exposed in present banks of incised channels. The Rio Puerco has undergone several major erosional-aggradational episodes during the past 2,500 years (Fig. 5). Major channels are nearly as large as the modern arroyo and similar in shape (channels I and II of Fig. 5). Smaller channels are similar to the modern inner channel (Fig. 5, channels III and IV). The facies in the smaller channels indicate that the channels meandered and shifted laterally like the modern inner channel. The larger channels, however, appear to have had wide, nearly flat, braided bottoms or low point bars with little vegetation, unlike the modern inner point bars and inner floodplain. As the major channels aggraded along the lower Rio Puerco, inner channels formed and became deep, narrow, relatively straight features dominated by coarser pebbly sand contributed by runoff from the valley margins. Flow from the headwaters commonly no longer reached the nearly aggraded channels. Locally-derived, reddish-brown clay-rich sediment completes the channel fills.

The fourth most extensive geomorphic features storing sediments within the Rio Puerco drainage are alluvial aprons developed along the flanks of the mountains and large mesas. Most of these features retain their original geomorphic fan-shaped form, although remnants of earlier fans exist locally, particularly in the northern subbasins (Bryan and McCann, 1937). These fans generally are more coarse-grained, more poorly sorted, and more locally derived than the fluvial-alluvial plain of the more extensive basin fill.

Stream terraces also store sediment along much of the Rio Puerco and along major tributaries, but they are discontinuous and/or buried by alluvial aprons or even other terraces (Figs. 2, 6). Most of the terraces are composed of coarse sand and gravel, but some of them have finer-grained floodplain facies and resemble the older alluvial-plain facies of the basin fill. The terraces range in thickness from 4 to 30 m.

Storage of sediment within the incised arroyos of Rio Puercc and many tributaries consists of inner channel and inner floodplain facies (Fig. 4). The floodplain of the Rio Puerco, developed since the large floods of the 1920's and 1930's, stores approximately 0.03 km^3 of sediment. The facies are primarily point bars, natural levees, backbasins, and oxbows, with minor sand plugs, eolian dunes, and arroyo-wall-collapse rubble (c.f. Shepherd, 1985). The floodplain is scoured and aggrades up to 1C cm during overbank flood events each year.

Unseen below the present Rio Puerco inner channel and floodplain are up to 6 m of coarser pebbly sand primarily laid down after the stream scoured the arroyo during large historic floods (Heath, 1983). Apparently much of the sediment stored in these deposits was in motion only during major floods and became stored again as the floods waned.

Flows within the inner channel of the Rio Puerco mobilize and store sediments in alternating bars, point bars, and ripples. Because much of the sediment in the channel is fine grained, no large megaripple (dune) forms occur. Nests of arroyo wall rubble and armored mud balls are common. The bedforms are commonly preserved as flow wanes and the bulk of the sediment remains in the channel until the next flow occurs. Minor amounts of sand and clay are blown out of the channel by the wind and are stored outside the channel in climbing dunes on the margins of the arroyo.

DISCUSSION

The Rio Puerco is not unique in the amount or history of sediment storage, but the amount of exposure of the stored sediment is unusual. Tectonic subsidence of the Albuquerque basin played a major role in storage of sediment before the streams integrated and flowed farther south. Since then, climatic influences have played a major role in sediment transport and storage. The amount of topographic relief developed on stored but erodible sediments indicates that the lack of adequate amounts of water limits the transport of sediment out of the basin.

The general processes of moving sediment from valley margins to valley floor and down channels appear to be straight-forward, but along each step of the way storage for decades or even thousands to hundreds of thousands of years may occur due to the lack of water with adequate energy to move the sediment further. Development of calcic soils increases the thresholds for movement even more.

Within the channel of the Rio Puerco, longitudinally (downstream) decreasing flow results in increased sediment concentrations in lower reaches and sediment deposition as water is lost to the bed. Therefore, sediment delivery downstream is inefficient during low flow. Flash floods erode quantities of channel sediment, but much of it is redeposited downstream within the channel or along the inner floodplain so that sediment delivery to the Rio Grande also is inefficient during high flow.

Preservation and storage of fluvial sediments in terraces is probably related to their position along the valley margins, their commonly coarse-grained cover, and in some cases, to their bedrock-defended lower margins. The coarse facies suggest that the Rio Puerco was more competent during these episodes and that sediment delivery was more efficient. Much more sand and finer-sized sediment was completely removed from the drainage basin during these episodes. Moreover, the terraces occur in a stepped sequence within valleys, indicating that the valleys themselves were eroded through proviously deposited sediments during episodes of increased efficiency of transport.

The facies of alluvial-fluvial basin fill also suggest more competent streams crossing the basin in the past 1-3 Ma (and probably longer) and efficient sediment delivery at least in the major channels. However, over the entire alluvial plain, both

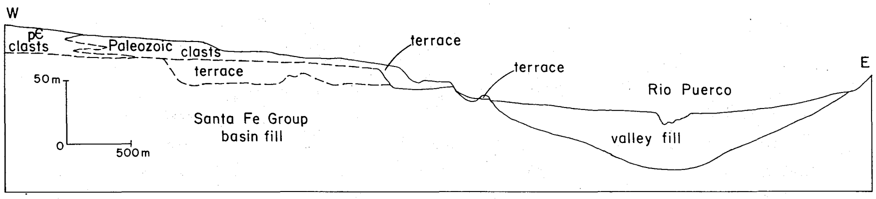


Fig. 6. Schematic cross section of terraces and valley fill near 34°28'N. Buried terrace is from axial Rio Puerco. Terrace overlying it and small terrace to east contain Paleozoic clasts from a major western tributary. The major terrace interfingers with an alluvial apron containing Precambrian clasts from the Ladron Mountains. Modified from Love and Young (1983) with NMGS permission.

fluvial and non-fluvial sediments accumulated during a long time span even with an axial Rio Grande transporting sediments to basins farther south. Therefore the overall efficiency of the Rio Puerco drainage system was less than after incision of the Puerco valley began.

The volume of sediment removed from the headwaters during the past 3 Ma (on the order of 2150 km^3) is impressive, but all of it could be accommodated in the upper 1000 m of fill in the western side of the Albuquerque structural basin. The amount of erosion to fill the basin, which locally is more than 6.5 km deep, is even more impressive, considering almost all the old sediment remains buried in the basin.

Recycling sediments at present generally goes from larger geomorphic features to smaller geomorphic features. Sediment from basin fill, terraces, alluvial aprons, soils, and valley fill is eroded to be stored either in alluvial fans or within the modern arroyos. But within the mainstem Rio Puerco, much of the sediment is recycled from erosion of the adjacent channel margins. The present hierarchy of quantities of stored sediment is due to the history of the drainage basin. Analysis of sediment delivery and storage would have been different in the past. When the basin-wide alluvial plain was aggrading, valley-fills and terraces were nonexistent in the "middle" and "lower" parts of the drainage and channel facies were different. In the future, as stream valleys deepen and widen, much geologic evidence of changes in sediment storage will be destroyed and simpler average rates of landscape denudation could be derived.

ACKNOWLEDGMENTS

This study summarizes data compiled by Doug Heath, Jim Boyle, Sylveen Robinson-Cook, John Young, Isam Amin, Phil Coleman, and Ghavam Mostafavi over several years of sponsorship by the New Mexico Bureau of Mines and Mineral Resources. The geologic history of the Rio Puerco drainage basin and Albuquerque structural basin is based on numerous discussions with John Hawley and Rick Lozinsky. I am grateful to John Hawley, Rick Lozinsky, and to Dick Hadley for reviewing the manuscript. I thank Cherie Pelletier and Russell Wood for drafting the figures and Lynne McNeil for helping to type the manuscript. The New

Mexico Geological Society granted permission to reproduce Figs. 5 and 6.

REFERENCES

Amin, I.E. (1983) Modeling of sediment transport in Rio Puerco, New Mexico. MSc Thesis, New Mexico Inst. Mining & Technol., Socorro, New Mexico, USA.
Armstrong, R.L., Speed, R.C., Graustein, W.C. & Young A.Y. (1976) K-Ar dates from Arizona, Montana, Nevada, Utah and Wyoming. Isochron/West 16, 1-5.
Bachman, G.O. & Machette, M.N. (1977) Calcic soils and calcretes in the southwestern United States. USGS Open-file Rept. 77-794.
Bachman, G.O., Marvin, R.F., Mehnert, H.H. & Merritt, V. (1975) K-Ar dates of Los Lunas and Albuquerque basalts. Isochron/West 13, 3-4.
Bachman, G.O. & Mehnert, H.H. (1978) New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico. Bull. Geol. Soc. Am. 89, 283-292.
Bondurant, D.C. (1951) Sedimentation studies at Conchas Reservoir in New Mexico: Am. Soc. Civ. Engr. Trans. 116 (2466), 1283-1295.
Bryan, K. (1928) Historical evidence of changes in the channel of the Rio Puerco, a tributary of the Rio Grande in New Mexico. J. Geol. 36, 265-282.
Bryan, K. & McCann, F. T. (1937) Successive pediments and terraces of the upper Rio Puerco in New Mexico. J. Geol. 44, 145-172.
Burkham, D.E. (1966) Hydrology of Cornfield Wash area and effects of land-treatment practices, Sandoval County, New Mexico, 1951-1960. USGS Wat. Sup. Pap. 1831.
Clemons, R. E., Kelley, R. W., Kottlowski, F. E., and Robertson, J. M. (1982) New Mexico highway geologic map. NMGS, scale 1:1,000,000.
Eidenbach, P.L. (ed) (1982) Inventory survey of the lower Hidden Mountain floodpool, lower Rio Puerco drainage, central New Mexico. Human Systems Research, Inc., Tularosa, New Mexico, USA.
Elliot, J.G. (1979) Evolution of large arroyos: The Rio Puerco of New Mexico. MS Thesis, Colorado State University, Fort Collins, Colorado, USA.
Gabin, V.L. & Lesperance, L.E. (1977) New Mexico climatic data: Precipitation, temperature, evaporation, and wind, monthly and annual means 1850-1975. W.K. Summers & Associates, Socorro, New Mexico, USA.
Grimm, J. (1985) Late Cenozoic geomorphic history of the Lobo Canyon area of the Mount Taylor volcanic field, Cibola County, New Mexico. MS Thesis, Univ. New Mexico, Albuquerque, New Mexico, USA.
Hawley, J.W., Bachman, G.O. & Manley, K. (1976) Quaternary stratigraphy in the Basin and Range and Great Plains Provinces, New Mexico and Western Texas. In: Quaternary Stratigraphy of North America (ed. by W.C. Mahaney), 235-274. Dowden, Hutchingson & Ross, Stroudsburg, Pa., USA.
Heath, D.L. (1983) Flood and recharge relationships of the lower Rio Puerco, New Mexico. NMGS Field Conf. 34, 329-337.
Izett, G.A., Obradovich, J.D., Naeser, C.W. & Cebula, G.T. (1981) Potassium-argon and fission-track zircon ages of Cerro Toledo

Rhyolite tephra in the Jemez Mountains, New Mexico: USGS Prof. Pap. 1199-D, 37-43.
Izett, G.A. & Wilcox, R.E. (1982) Map showing localities and inferred distributions of the Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada. USGS Misc. Inv. Ser. I-1325.
Kelley, V.C. (1977) Geology of the Albuquerque basin, New Mexico. New Mexico Bur. Mines & Min. Res. Mem. 33.
Kudo, A.M., Kelley, V.C., Damon, P.E. & Shafiqullah, M. (1977) K-Ar ages of basalt flows at Canjilon Hill, Isleta volcano, and the Cat Hills volcanic field, Albuquerque-Belen basin, central New Mexico. Isochron/West 18, 15-16.
Lambert, P.W. (1978) Upper Santa Fe stratigraphy and geomorphic features of the Llano de Albuquerque. In Guidebook to Rio Grande rift in New Mexico and Colorado (compiled by J.W. Hawley), 151, New Mexico Bur. Mines & Min. Res. Circ. 163, Socorro, NM, USA.
Lipman, P.W. & Mehnert, H.H. (1980) Potassium-argon ages from the Mount Taylor volcanic field, New Mexico. USGS Prof. Pap. 1124-B.
Lopez, L.S. (1982) The Rio Puerco Irrigation Company. New Mexico Hist. Rev. 57, 63-79.
Love, D.W. & Young, J.D. (1983) Progress Report on the late Cenozoic geologic evolution of the lower Rio Puerco. NMGS Field Conf. 34, 277-284.
Lozinsky, R. P., & Tedford, R. H., 1986, Stratigraphy of the Santa Fe Group (Oligo-Pleistocene) in the Gabaldon badlands, north-central New Mexico. Geol. Soc. Am. Abs. with Programs, vol. 18, no. 5, 391.
Machette, M.N. (1978) Geologic Map of the San Acacia quadrangle, Socorro County, New Mexico. USGS Geol. Map GQ-1415.
Machette, M.N. (1985) Calcic soils of the southwestern United States. Geol. Soc. Am. Special Pap. 203, 1-21.
Nordin, C.F., Jr. (1963) A preliminary study of sediment transport parameters, Rio Puerco near Bernardo, New Mexico. USGS Prof. Pap. 462-C.
Popp, C.J., Hawley, J.W., & Love, D.W. (1983) Radionuclide and heavy metal distribution in recent sediments of major streams in the Grants mineral belt. Final Rept. to Off. Surface Mining, U.S. Dept. Interior.
Schumm, S.A. & Lichty, R.W. (1965) Time, space and causality in geomorphology. Am. J. Sci. 263, 110-119.
Shepherd, R.G. (1985) Fluvial process and sediments, Rio Puerco, New Mexico. Third Internat. Fluvial Sed. Conf. Abs., 34.
Tedford, R.H. (1981) Mammalian biochronology of the late Cenozoic basins of New Mexico. Geol. Soc. Am. Bull. 92, 1008-1022.
US Army Corps of Engineers (1973) Rio Puerco and Rio Salado, New Mexico. Report on review survey for flood control and allied purposes. Albuquerque District, Albuquerque, New Mexico, USA.
US Bureau of Land Management (1972) Rio Puerco special project evaluation report. U.S. Dept. Interior, Bur. Land Management.
Wells, S.G., Bullard, T.F., Condit, C.D., Jercinovic, M., Jercinovic, D.E. & Lozinsky, R.P. (1983) Geomorphic processes on the alluvial valley floor of the Rio Puerco. Am. Geomorph. Field Gp. Field Trip Guidebook 1983, 37-39.
Wright, H.E., Jr. (1946) Tertiary and Quaternary geology of the lower Rio Puerco area, New Mexico: Geol. Soc. Am. Bull. 57, 383-456.