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GEOMORPHIC EFFECTS OF STREAM CHANNELIZATION ON THE RIO PUERCO NEAR LA VENTANA, NEW MEXICO, USA

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Abstract—In 1965, the New Mexico Department of Transportation channelized a 3.4-km section of the Rio Puerco near La Ventana, Sandoval County, New Mexico, with an artificial, straight 1.7-km-long channel to facilitate new highway construction. The channelization nearly doubled the slope of the stream while reducing the hydraulic radius of the channel. Geomorphic adjustments in the channelized reach were drastic and rapid, including incision, widening, and development of meanders. In 2006, after the channelized reach had incised to depths of at least 15 m, widened to at least 105 m, and developed a meander that threatened U.S. Route 550, the river was rerouted back into its natural channel. During the four-decade lifespan of the channelization, an estimated 6.2×10^5 m^3 of sediment was removed via erosion and delivered down the Rio Puerco. The sinuosity of the channelized reach increased from 1.000 to 1.093. Headward migration of a knickpoint in the channelized reach was retarded only by the presence of resistant bedrock underneath alluvium. A 1997 geological investigation of the then-active channelization accurately estimated sediment removal and predicted future geomorphic responses that were later observed. Geomorphic adjustments in the channelized reach and the Rio Puerco's natural channel continue at present and include stream slope adjustment in the natural channel, channel widening due to bank collapse, and development of soil piping leading to considerable sediment transport and likely perpetuating arroyo widening. The changes to the Rio Puerco fluvial system caused by the channelization will continue into the future until the river reaches new geomorphic equilibrium.

INTRODUCTION

The Rio Puerco, a mostly ephemeral tributary to the Rio Grande in central New Mexico, flows 240 km from its headwaters at 3,185 m (10,450 ft) ASL in the San Pedro Parks area of the Sierra Nacimiento northwest of Cuba to its confluence with the Rio Grande at 1,440 m (4,720 ft) ASL near Bernardo. In its uppermost 20 km, the stream is perennial; downstream (roughly starting at Cuba), its flow is intermittent or ephemeral. Downstream from Cuba, the Rio Puerco is an alluvial stream; that is, it flows over alluvium that it previously deposited. Throughout its alluvial course, it has incised a steep-walled, 10- to 16 m-deep arroyo into its alluvium. Rio Puerco arroyo incision began in the late 19th century. Reliable historical accounts show that the river had previously flowed over a broad floodplain in some reaches. Now, even in the largest floods observed in the 20th and 21st centuries, the river has not overflowed the current arroyo banks.

The Rio Puerco has a very high sediment yield, with the third-highest ratio of sediment load to annual discharge of any measured river on Earth (Gellis, 1997). Over an observation interval from 1948–1996, the Rio Puerco had an average annual sediment yield of 4.03×10^6 tonnes (t) and provided between 64% and 83% of the total sediment delivered by the Rio Grande to Elephant Butte Reservoir, approximately 84 km downstream of the confluence of the Rios Puerco and Grande. During that time interval, the Rio Puerco contributed only 2.3% to 5.6% of the total annual discharge of the Rio Grande into Elephant Butte Reservoir (Gellis, 1997). Suspended-sediment concentrations in excess of 400,000 mg/L have been observed in Rio Puerco waters (USGS, 2009). Average suspended-sediment concentrations in Rio Puerco waters are 79,000 mg/L (Bureau of Reclamation, 1996).

The wide valley of the Rio Puerco, particularly its late Holocene, pre-20th century floodplain, has long been a natural travel corridor in and through the watershed. Two of New Mexico's three interstate highways occupy portions of the Rio Puerco floodplain, and U.S. Route 550 (formerly New Mexico State Road 44) parallels the Rio Puerco for 33 km, mostly along the pre-20th century floodplain surface. Prior to 1965, this highway bypassed much of the Rio Puerco floodplain between La Ventana and Cuba via a steeper and more sinuous route east of the river and closer to the small communities of San Miguel, San Pablo, and Señorito (Fig. 1). In order to make a straighter, flatter, and safer highway, the New Mexico Department of Transportation (NMDOT) in 1965–1966 rerouted State Road 44 to the west, through a 500 m-wide bedrock-walled canyon of the Rio Puerco (Fig. 1). During this reroute, NMDOT channelized the Rio Puerco, cutting off a sinuous 3.4-km reach of the river with a 1.7-km straight channel. The Rio Puerco's geomorphic response to channelization began almost immediately and continued until NMDOT rerouted the river back into its natural channel in 2006. Slower geomorphic adjustments continue at present. The river's six-decade response to anthropogenic alterations provides unique lessons in stream power, fluvial adjustment, sediment supply, and channel behavior, as well as a cautionary tale about the value of cross-disciplinary understanding of geomorphic concepts prior to construction projects.

Geologic Setting

The study area lies at the southeast margin of the San Juan Basin and near the boundary of the Colorado Plateau and Southern Rocky Mountains physiographic provinces. The formerly diverted reach of the Rio Puerco is located between La

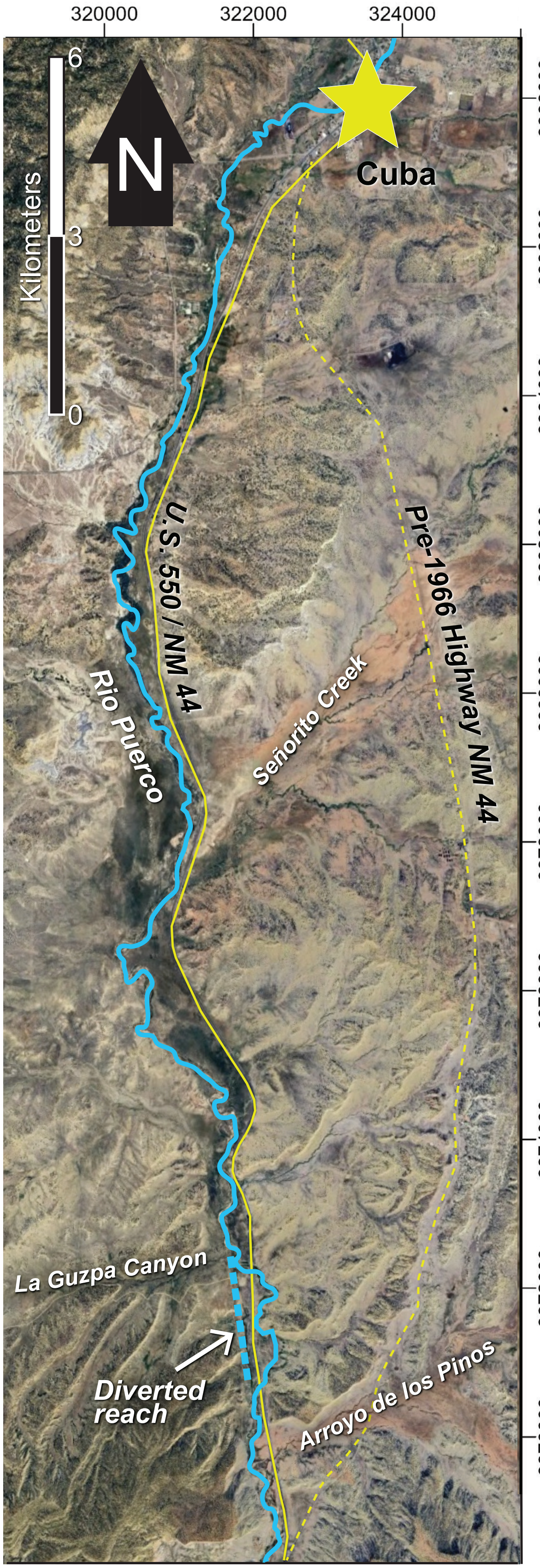

Figure 1. Annotated aerial photograph showing the Rio Puerco, the diverted reach of the Rio Puerco, the current alignment of U.S. Route 550 (formerly State Road 44), and the pre-1966 alignment of New Mexico State Road 44. NAD 1983 Zone 13N coordinates shown.

Guzpa Canyon to the north and Arroyo de los Pinos to the south in a south-flowing section of the river 17 km south-southwest of Cuba, and 4.5 km north of the former townsite of La Ventana, Sandoval County, New Mexico. The pre-20th century floodplain in this reach is 250 to 780 m wide between bedrock hillslopes and cliffs. The floodplain surface is flat when measured perpendicular to stream flow direction and has a downstream slope of 0.0045 (0.26°). Alluvium forming the pre-20th century floodplain in this reach comprises weakly consolidated mud, silt, and sand in varying proportions; the most common composition is sandy muddy silt. Alluvium contains weakly developed paleosols with A and Bw horizons and an A-Bw-C entisol at its surface. Pebbles make up less than 1% of the alluvium. Alluvium thickness ranges from 7 m to at least 16 m in this reach. Bryan and McCann (1936) report alluvium thicknesses up to 25 m in the same unit nearby.

Terraces of the Rio Puerco are found in and near this reach. The oldest known terrace in the reach stands 65 m above the modern Rio Puerco (the "La Jara" terrace of Bryan and McCann [1936]). A younger and more extensive terrace, the "Rito Leche" terrace of Bryan and McCann (1936), stands 30 to 35 m above the modern Rio Puerco. Both of these terraces are capped by deposits of 1.5 to 4 m of sand, gravel, cobbles, and boulders deposited by the ancient Rio Puerco during episodes of greater stream power, presumably in the Late Pleistocene. Pebbles, cobbles, and boulders in these deposits are dominated by clasts of granite and granitic gneiss derived from the Sierra Nacimiento with smaller proportions of amphibolite, metapelite, biotite schist, and limestone.

Bedrock in the affected reach includes two Late Cretaceous sedimentary units: the Menefee Formation, containing interbedded mudstones and arenites with minor thin coals, and the overlying La Ventana Tongue of the Cliff House Sandstone, dominated by arenites with minor mudstones. Bedrock units dip to the north at 5° to 7° (Woodward and Schumacher, 1973).

Elevations in the immediate area of the channelized reach range from 1,990 to 2,260 m (6,530 to 7,410 ft) ASL. The streambed at the upstream point of diversion is at 2,007 m (6,583 ft) ASL, and at the downstream point of confluence between the channelized reach and the natural channel is at 1,993 m (6,537 ft) ASL. The Rio Puerco's natural channel is incised 8 to 17 m into the pre-20th century floodplain in this reach.

HISTORY

For most of a century, the Rio Puerco has been the topic of scientific and engineering studies regarding erosion control (e.g., Bryan and Post, 1927; Nordin, 1963; Bureau of Reclamation, 1996) and the history of erosion (e.g., Bryan, 1928; Aby et al., 1997; Love, 1997; Bierman et al., 2005; Aby, 2017; Gellis et al., 2017). Most workers agree with Bryan's (1928) early assessment, based on 19th-century surveys and eyewitness accounts, that the Rio Puerco was unincised or was a discontinuous arroyo with alternating reaches of shallow incision and unincised reaches until around 1885. Love (1997) presents a contrasting assessment, stating that several early and middle

19th century reports describe a Rio Puerco already incised 3 to 8 m. Early accounts from the study area note that in 1870 at San Luis, located 24 km downstream of the study area, one person "could build a dam for diverting the river by felling a cottonwood tree across the channel" (Bryan, 1928). A native of La Ventana, 5 km downstream of the study area, recounted to Bryan (1928) that the Rio Puerco was incised about 8 feet (2.4 m) in the 1870s; he also remembered that the Rio Puerco was unincised and flowed over a smooth plain at its confluence with Señorito Creek, 7 km upstream of the study area. A resident at Cabezon, 35 km downstream from the study area, recalled that the Rio Puerco had incised deeply enough to cause his well to go dry sometime between 1885 and 1890. Most human settlements in the Rio Puerco valley downstream of Cuba were abandoned in the early and middle 20th century due to the inability to irrigate from the river after its deep downcutting.

Since at least the early 20th century, the Rio Puerco downstream from Cuba has been an intermittent or perennial stream. Data from a gaging station at Guadalupe, 38 km downstream from the study site, show that the Rio Puerco flowed only 51% of days in the observation interval from 1951–2021 (USGS Station 08334000). Like most intermittent streams in semiarid regions, the Rio Puerco's flows usually occur after spring snowmelt or summer thunderstorms. Low-frequency, high-magnitude flow events in the Rio Puerco have the capacity to change the landscape through incision or lateral migration. Several such events have been observed and described in the literature (e.g., Love, 1992; Griffin and Friedman, 2016). Analysis of historical aerial photos shows that some Rio Puerco cutbanks have laterally migrated up to 80 m between 1997 and 2023, giving a minimum migration rate of 3.1 m/yr.

Despite the Rio Puerco's well-documented history of dynamic erosion, in 1965, NMDOT realigned State Road 44 (now U.S. Route 550) just north of La Ventana to follow the river's valley atop its pre-20th century floodplain. Near the southern end of the realignment, where the Rio Puerco is constrained through a topographically confined valley with steep bedrock walls, the new route crossed the river twice and narrowly skirted the edge of a meander loop (Fig. 2). In order to avoid the costs of building two bridges over the Rio Puerco, NMDOT instead rerouted the river via a straight diversion that cut off the broad arc of the river. The new highway was conveyed across the former channel on earthen berms. The slope of the Rio Puerco's natural channel in this reach was likely no greater than 0.0040 (Coleman et al., 1997). The slope of the artificial diversion was approximately 0.0074. The width of the incised natural channel at the affected reach is 50 to 150 m. The diversion channel was 18 m wide at its upstream diversion point and narrowed to 6 m wide within its first 30 m, with an initial constructed depth of 6 m (Coleman et al., 1997). The volume of sediment excavated for the channel diversion in 1965 was approximately 2.44×10^5 m^3. The artificial diversion rejoined the natural channel of the Rio Puerco just downstream of the southern highway crossing (Fig. 2).

In 1997, geologists from the U.S. Geological Survey, New Mexico Environment Department, and New Mexico Bureau of Geology and Mineral Resources studied the channelized reach (Coleman et al., 1997), finding that the Rio Puerco's geomorphic response to channelization had been immediate and drastic. Coleman et al. (1997) also provided valuable maps and graphs of the state of the river in the mid-1990s. Coleman et al. (1997) estimated that 3.99×10^5 m^3, or 6.45×10^5 t, of sediment had been eroded from the channelized reach between 1965 and 1994. By 1973, the channelized channel had widened to over 30 m and had cut down into Cretaceous bedrock. By 1994, it was at least 91 m wide and had developed significant meanders. One meander's cutbank had migrated to within 28 m of the realigned highway. The planned widening of the highway from two to four lanes in 2000 would bring the highway dangerously close to this cutbank. (As of 2024, this 14-m-tall cutbank is 11 m from the edge of the highway embankment, and 18 m from the edge of the pavement). Overall erosion likely would have been greater had the channelized reach not incised into resistant Cretaceous sandstones that formed a knickpoint that was migrating upstream at a rate of approximately 1 m/yr (Coleman et al., 1997).

In the early 2000s, NMDOT built two new bridges across the natural channel of the Rio Puerco to replace the earthen berms that had conveyed the highway across this channel since 1965. Once the bridges were operational, NMDOT redirected the waters of the river through the natural channel that had been dry for four decades. The artificial channel remains, but is cut

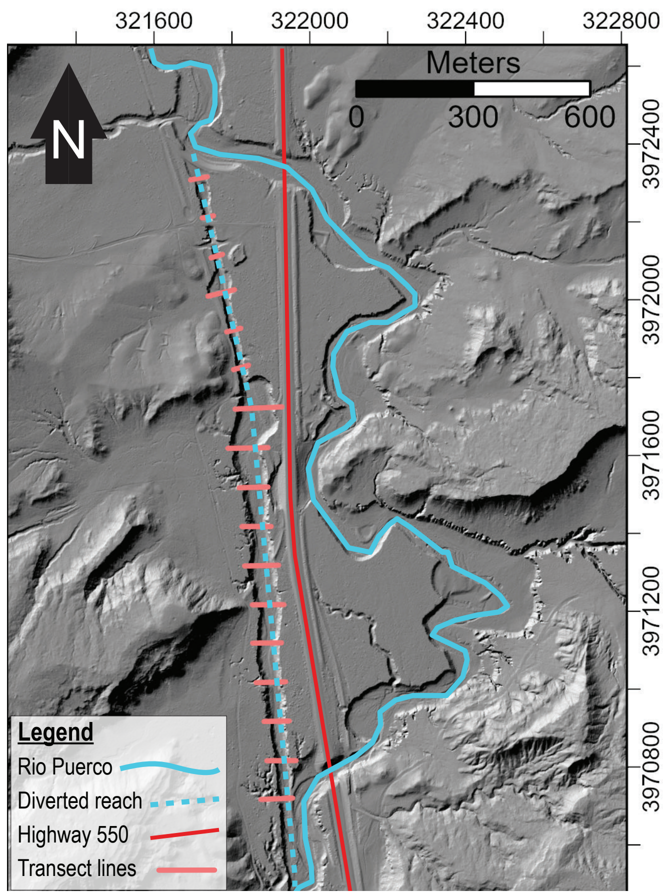

Figure 2. Annotated shaded relief map of the study area derived from 1-meter DEM data. Transect lines are spaced at 100 m intervals. NAD 1983 Zone 13N coordinates shown.

off from the Rio Puerco by an earthen dam at its upstream end. At the downstream confluence point where the channelized reach rejoined the natural channel, there had been significant downcutting of the streambed. To prevent upstream migration of a knickpoint through the natural channel, NMDOT installed a series of rock steps in the streambed immediately beneath the downstream bridge. As of 2021, the wire gabions comprising these structures are being broken during flow events and downstream scour is occurring (Loberger et al., 2021) as the natural channel adjusts to new equilibria.

METHODS

Geospatial analyses were performed in ArcGIS Pro v3.3.1. Elevation data were obtained from 1-m DEMs derived from LiDAR surveys in 2017 and 2018 and downloaded from Lidar-Explorer (USGS, 2024). Individual DEM rasters were combined into a single DEM with the Mosaic to New Raster tool. Stream thalwegs were placed after using the Fill, Flow Direction, and Flow Accumulation tools (using a bin size of 50,000), then using the Set Null tool to create a raster of stream bottoms. This raster was vectorized with the Stream to Feature tool. Transect lines perpendicular to the channel were added in ArcGIS Pro at 100-m intervals through the formerly channelized reach (Fig. 2). Topographic profiles along transects and stream channels were created with the Elevation Profile tool in Exploratory 3D Analysis. Elevation and distance data from the topographic profiles were downloaded as CSV files, and further analyzed in Microsoft Excel. Sinuosity between two points in the stream was calculated with the formula:

$$\text{Sinuosity} = \frac{\text{channel length}}{\text{straightline downvalley length}}$$

The volume of material (V) that was eroded from segments within the channelized reach was calculated with the formula:

$$V = \{[E_{max} - (\frac{(E1 + E2)}{2})] \times (D_2 - D_1)\} * L$$

E_{max} is the elevation of the upper edge of the eroded channel, E_1 and E_2 are the elevations of the bottom of the transect segment at each end of the segment, and D_1 and D_2 are the distances from the transect origin to the beginning and ending endpoint of the transect segment respectively (Fig. 3). The value L represents the length between transect lines in meters. Finally, the volume of all segments was summed for a total sediment volume eroded from the channelized reach.

RESULTS

Channel Slopes

Profiles of the thalwegs of the natural channel and channelized reach channel are shown in Figure 4. The slope of the natural channel between the upper and lower diversion points is 0.00419, close to the slope of 0.004 calculated from topographic maps by Coleman et al. (1997). As seen in Figure 4, the engineered rock steps in the lowermost segment of this reach form a knickpoint. Below these steps, significant incision occurred between 1965 and 2006. The prediversion slope of this reach of Rio Puerco likely was closer to the 0.00349 value that exists above the rock steps (Fig. 4). The channel's slopes above and below these steps are in disequilibrium.

The slope of the thalweg of the channelized reach between the upper and lower diversion points is 0.00721, again close to Coleman et al.'s (1997) estimate of 0.0074. The bedrock knickpoint in the channelized reach is apparent in Figure 4; the channel's slopes above and below this knickpoint are in disequilibrium.

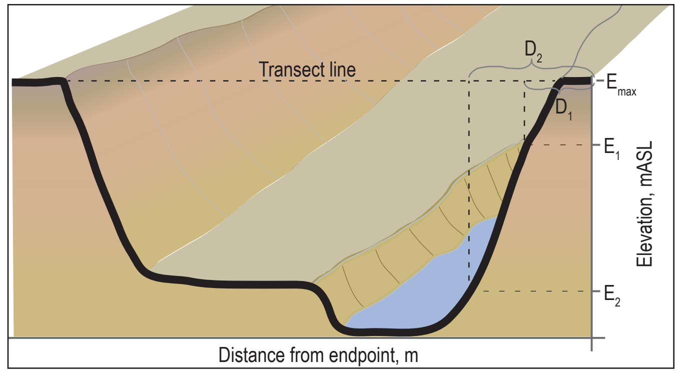

Figure 3. Schematic diagram of incised channel showing distances and elevations analyzed in volume calculations. E_{max} is the elevation of the upper edge of the eroded channel, E_1 and E_2 the elevations of the bottom of the transect segment at each end of the segment, and D_1 and D_2 the distances from the transect origin to the beginning and ending endpoint of the transect segment. The cross-sectional area of a transect segment is calculated as

$$\{[E_{max} - (\frac{(E1 + E2)}{2})] \times (D_2 - D_1)\}$$

Sinuosity

The sinuosity of the natural channel between the upper and lower diversion points is 1.855. The sinuosity of the channelized reach is 1.093. For comparison, the Rio Puerco's sinuosity in the 5 km above the formerly diverted reach is 1.546 with a slope of 0.00274, and sinuosity in the 5 km below the formerly diverted reach is 1.847 with a slope of 0.00323.

Sediment Removal

By measuring the cross-sectional area of the channelized reach at 100-m intervals, multiplying each area by 100 m to estimate a volume, and then summing the volumes for each 100-m section, a total sediment volume of 859,233 m^3 was estimated to have been removed from the channelized reach between 1965 and 2017, when LiDAR data used to create DEMs for this study were collected. The original excavation removed approximately 243,524 m^3 (Coleman et al., 1997), meaning that 615,709 m^3 of sediment was removed via stream erosion. Coleman et al. (1997) estimated that by 1997, erosion had removed 399,268 m^3 of sediment from the channelized reach. Subtracting the total estimated volume removed

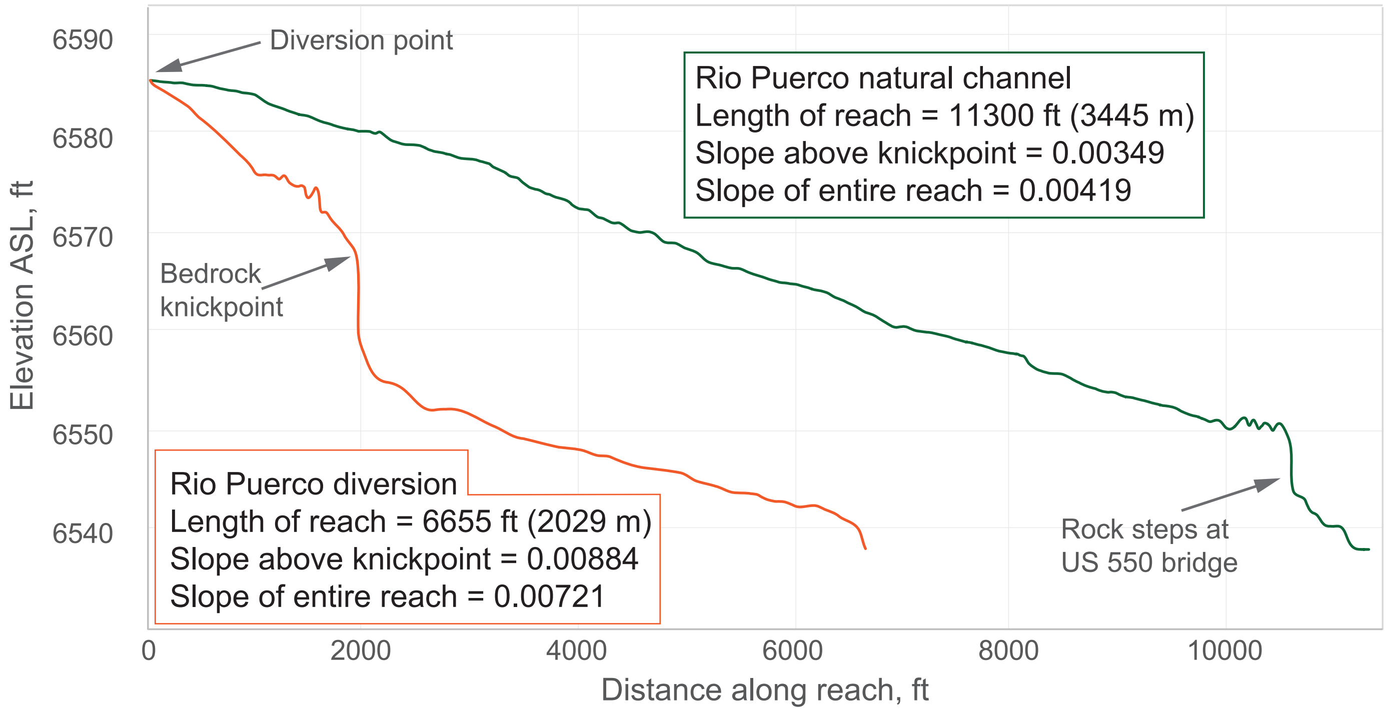

Figure 4. Stream profiles of the natural channel of the Rio Puerco (green) and the channelized reach (red) between the upper and lower diversion points.

by erosion in 2017 minus the 1997 eroded volume estimate of Coleman et al. (1997) shows that 216,441 m^3 of sediment was eroded from the channelized reach between 1997 and 2017, the majority of which was likely to have been eroded between 1997 and the abandonment of the channelized reach in 2006.

The total volume of eroded sediment, ~6.2 x 10^5 m^3, has a mass of approximately 890,000 t assuming the average sediment density of 1.44 t/m^3 used by Coleman et al. (1997) in the same setting. Assuming a 40-year interval of streamflow through the channelized reach (1966 through 2005), then the average rate of sediment erosion was 22,320 t/yr, nearly the same as Coleman et al.'s (1997) estimated rate of 25,096 t/yr for the interval from 1966 through 1996. These estimates are based on the volume of the channelized reach and do not include sediment loss through soil piping, discussed below. Therefore, they are conservative minimum estimates.

Soil Piping

Soil piping is a complex process with no single meaning in the geomorphology or hydrodynamics literature. Herein, the term refers to the formation of elongate voids (soil pipes) by the concentrated flow of water in the subsurface through soils or unconsolidated sediment such as the pre-20th century alluvium of the Rio Puerco. The term is also applied hesitatingly and with caution due to the phenomenon's observed occurrence in media other than soil, but the author wishes not to propose new jargon even though it requires misuse of the term "soil."

Soil pipes act as conduits for water and sediment. The mechanisms of soil piping are complex and include a number of geologic, hydrologic, pedologic, climate, and biotic factors (Bernatek-Jakiel and Poesen, 2018). Once soil pipes form, they can enlarge upwards via roof collapse, eventually reaching the ground surface and causing collapse features often called sinkholes, a term used herein with caution because such features are not related to karst processes. An individual soil-piping sinkhole can coalesce with others to form an elongate collapse feature called a blind gully. Soil pipes, sinkholes, and blind gullies are observed in and on the pre-20th century alluvial surface of the Rio Puerco near the channelized reach (Fig. 5). Blind gullies are up to 9 m deep, sinkholes up to 7 m in diameter (Fig. 6), and soil pipes up to 3 m in diameter. Soil pipes' lengths were not investigated. A 2.5-ha area of pre-20th century alluvium near the center of the west side of the channelized reach displays polygonal patterned ground, with polygons' maximum lengths ranging from 11 to 74 m (Fig. 7). The development of polygonal patterned ground in the study area likely is due to the lowering of local water tables after the downcutting of the channelized reach followed by desiccation of clay minerals in floodplain alluvium leading to shrinking sediment volume along nascent soil fractures.

Where soil pipes intersect with vertical or steep arroyo walls, there is evidence for sediment transport into the Rio Puerco and the formerly channelized reach in the form of sediment fans or aprons (Fig. 8). The volume of sediment delivered via soil pipes is not quantified but warrants further study.

Soil pipes and sinkholes are observed in Rio Puerco alluvium outside the channelized reach, but seem to be less common. Blind gullies have not been observed outside the area of the channelized reach, but may be present. Hobbs et al. (2023) report soil pipes in alluvium of Cañon Largo, a natural and nonchannelized arroyo system outside the Rio Puerco watershed in Sandoval and Rio Arriba Counties, New Mexico,

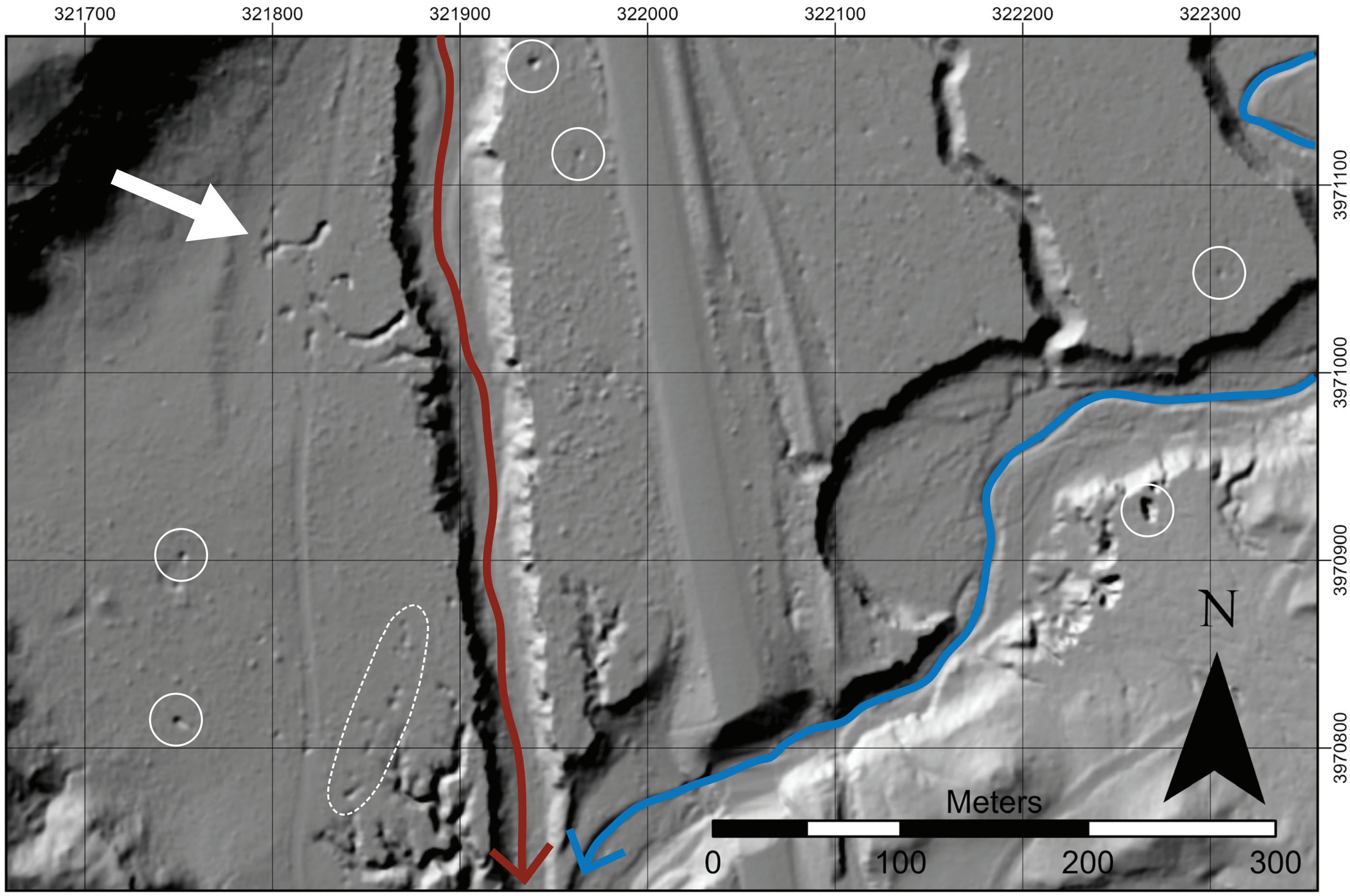

Figure 5. Annotated shaded relief map of the southern end of the channelized reach near its junction with the natural channel of the Rio Puerco. U.S. Route 550 runs north-northwest through the center of the map. White arrow indicates blind gullies. White circles indicate soil-collapse sinkholes related to soil piping. Dashed white ellipse indicates linear alignment of soil collapse sinkholes that likely formed along a linear soil fracture. Thalwegs of the channelized reach (red line) and Rio Puerco (blue line) are indicated.

indicating that the features can form in local watersheds that lack extensive anthropogenic alteration.

DISCUSSION

The diversion of the Rio Puerco disrupted the balance of depositional (resisting) and erosional (driving) factors that existed in the study area. These factors are simplified by Lane (1955) and visually represented by Borland (1960; Fig. 9). Using factors from that simplified model, the diversion immediately increased the slope of the Rio Puerco, tipping the system into a downcutting (degradational) episode in the channelized reach. By 1994, portions of the channelized reach had developed meanders, thereby reducing the slope and likely increasing sediment load by cutbank collapse. These factors initiated an aggradational phase in the lower diversion. Had the diversion remained active, the resisting and driving factors would have balanced at an equilibrium after some time, assuming the absence of other external changes. This hypothetical equilibrium likely would have had broader effects than those observed in the 40-year lifespan of the diversion, including geomorphic responses upstream and downstream of the channelized reach. It should be noted that the schematic in Figure 9 and the discussion above are simplified models that do not explore the intricacies of stream dynamics that rely on the foundational early work of quantitative geomorphologists (e.g., Leopold and Miller, 1956; Chorley, 1957; Schumm and Hadley, 1957).

Although animal burrows (Carroll, 1949), casts of dead roots (Carroll, 1949), overgrazing (Downes, 1946; Kingsbury, 1952), and dispersive soils (Dunne, 1990) all have been listed as potential causes for soil pipes in semiarid environments, soil fractures seem to play an important role in soil piping in the pre-20th century alluvium of the Rio Puerco. The importance of soil fractures in soil piping has been documented in other semiarid alluvial settings (e.g., Heede, 1971), and the linear nature of blind gullies, sinkhole alignments, and polygonal patterned ground in the study area support a fracture origin.

Downstream Effects

The downstream effects of the diversion are difficult to quantify beyond the estimated volumes of sediment delivered during its 40-year lifespan. The late 20th century timing of the diversion coincides with arroyo widening, increased vegetation, and floodplain development documented by trenching and dendrochronology studies in the lower Rio Puerco (Friedman et al., 2015). Therefore, it is difficult to differentiate the increased sediment supply provided to the Rio Puerco by the diversion from the sediment whose storage in the lower Rio Puerco had already begun before the diversion occurred.

Upstream Effects

The upstream effects of the diversion likely include knickpoint migration and increased downcutting. Upstream effects were limited by the presence of shallow bedrock in the channelized reach which retarded upstream knickpoint migration to a rate of approximately 1 m/yr (Coleman et al., 1997). Love (1992) documented the absence of upstream knickpoint migration in a Rio Puerco meander cutoff 2 km upstream of the channelized reach. The drop across that upstream cutoff was 1.7 m and the streambed essentially reached the precutoff slope again via gradual adjustments within one flow season (Love, 1992). The cutoff occurred approximately 23 years after the diversion. Further research is needed to support or deny causative links between the diversion and the cutoff.

Limits on Erosion

The channelized reach of the Rio Puerco provides a case study in which aspects of the long-accepted arroyo cycle can be observed. The arroyo cycle refers to the inherently unstable and cyclic nature of arroyo morphology, including stages of floodplain aggradation, arroyo cutting, and arroyo filling. The channelization of the Rio Puerco by NMDOT in 1965–1966 effectively provided an artificial start to the arroyo cycle at the arroyo-cutting stage. Though the initial "arroyo cutting" was anthropogenic, arroyo cutting in the channelized reach continued after diversion due to increased stream power in the channelized reach. The increase in stream power was mostly caused by an increase in slope, though the decrease in both hydraulic radius and channel roughness likely contributed (Simon, 1989).

Figure 6. Photograph of soil collapse sinkhole in pre-20th century alluvium of the Rio Puerco along the channelized reach. Sinkhole is 7 m wide and at least 4 m deep.

In the arroyo cycle, as arroyo incision continues, arroyo walls become more susceptible to collapse (Simon and Collinson, 2002; Friedman et al., 2015), increasing arroyo width. This process occurred at the channelized reach, where the depth increased by as much as 280%, and the width by as much as 1,800% from the channel's initial dimensions.

In natural arroyos as well as the channelized reach, as channel width increases, flow depth decreases. Stream power likewise decreases, causing a transition from incision to deposition (Schumm and Hadley, 1957; Friedman et al., 2015). This transition allows and then is facilitated by the establishment of vegetation along the nascent floodplain or in developing meander bends (Schumm and Hadley, 1957; Gellis et al., 2012). A 1997 aerial photograph (the only available aerial photograph

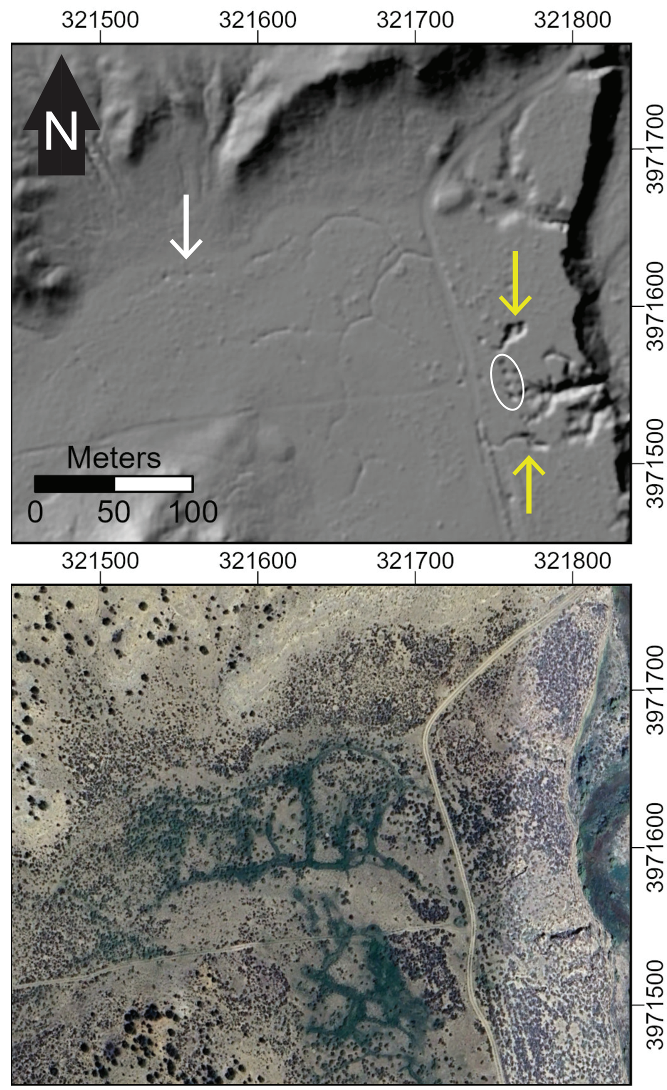

Figure 7. Annotated shaded relief map (top) and aerial photograph (bottom) of an area of polygonal patterned ground along the channelized reach. White arrow marks three soil collapse sinkholes along a linear depression interpreted as a soil fracture. Yellow arrows mark blind gullies. White ellipse marks linear alignment of soil collapse sinkholes. In bottom photograph, note the alignment of denser and greener vegetation along the same patterns of topographic depressions marking patterned ground polygon boundaries. These vegetation-indicated features are visible in every aerial photo of this site since at least 1996. NAD 1983 Zone 13N coordinates shown.

Figure 8. Photograph of the east bank of the Rio Puerco near the channelized reach showing soil pipes debouching into the Rio Puerco. White arrow marks 2 m-diameter soil pipe with an apron of sediment at its mouth indicating sediment delivery through soil pipes. Yellow arrow marks 3 m-diameter soil pipe. The large sediment apron in the center is at the base of a blind gully developed between the Rio Puerco and U.S. Route 550 and later breached by the eastward migration of the Rio Puerco arroyo wall. Photograph taken towards the east-northeast at approximately 4:30 P.M. on June 21, 2024, from approximately 35.8476°, −106.9703°.

of the channelized reach between 1965 and 2006) show the presence of shrub and possible small tree vegetation in the meanders of the channelized reach.

As deposition continues in the arroyo cycle, stream sinuosity increases, sometimes leading to the development of cutbanks into original arroyo walls, further increasing the sediment supply of the deposition system. Based on analysis of a 2005 aerial photograph, one 500 m-long reach of the channelized stream had attained a sinuosity of 1.248 where the largest meanders developed. This location is also where a cutbank on the east side of the channelized reach threatens U.S. Route 550.

Portions of the lower channelized reach had begun the arroyo filling stage when streamflow was returned to the natural channel in 2006. Other portions were still relatively narrow and low sinuosity, indicating that stream response was variable over length scales of less than 100s of meters and time scales of less than decades. However, the system was beginning to develop a floodplain and store sediment, like the majority of the Rio Puerco in its alluvial reach since roughly 1930 (Friedman et al., 2015). The texture of that sediment is unknown and warrants further study.

The upstream portion of the channelized reach was graded to a bedrock knickpoint (Fig. 4) that Coleman et al. (1997) reported was migrating upstream at a rate of 1 m/yr. At the same time, the upstream portion also had developed a short meander that had widened the channel to a width of 55 m. Given enough time, it is likely that the bedrock knickpoint would have migrated through the channelized reach entirely and into the natural channel above the diversion until the system found new equilibrium among stream power, discharge, slope, sediment supply, and roughness. The natural channel's slope, bedforms, sediment storage capacity, and vegetation likely experienced change after the Rio Puerco's flow were returned to it. Those effects were not included as part of this study but are worthy of future work.

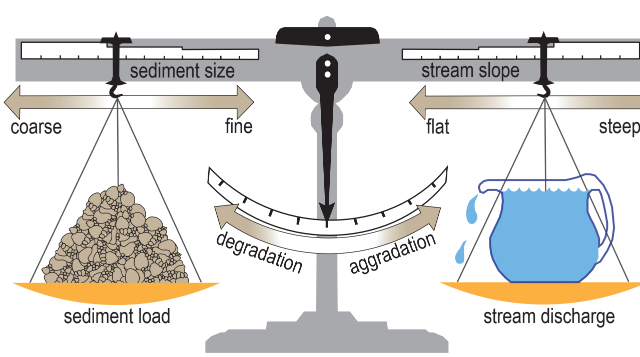

Figure 9. Schematic model of the driving and resisting factors affecting stream degradation (incision) and aggradation. In this simplified model, a change in the value of sediment size, stream slope, sediment load, or stream discharge will tip the stream into disequilibrium unless it is counteracted by a change of a similar magnitude but opposite direction of another factor. For instance, an increase in stream discharge that coincides with an increase in sediment load might have no effect on stream balance. However, an increase in discharge with increase in sediment load will tip the balance towards degradation. The diversion of the Rio Puerco increased the river's slope with minimal effects on other factors, initially tipping the Rio Puerco system into a degradational state in the channelized reach. Modified from Rosgen (1996) after Lane (1955).

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View to the east along Almagre Arroyo from State Road 112. A cuesta of the Mesaverde Group in the middle distance; French Mesa forms the skyline on the left. (Mile 17.5 of Day 2 Road Log).