Processes of arroyo filling in northern New Mexico, USA

Jonathan M. Friedman[1,†], Kirk R. Vincent[2], Eleanor R. Griffin[2], Michael L. Scott[1], Patrick B. Shafroth[1], and Gregor T. Auble[1]

[1]*U.S. Geological Survey, 2150 Centre Avenue, Building C, Fort Collins, Colorado 80526, USA*

[2]*U.S. Geological Survey, 3215 Marine Street, Suite E-127, Boulder, Colorado 80303, USA*

ABSTRACT

We documented arroyo evolution at the tree, trench, and arroyo scales along the lower Rio Puerco and Chaco Wash in northern New Mexico, USA. We excavated 29 buried living woody plants and used burial signatures in their annual rings to date stratigraphy in four trenches across the arroyos. Then, we reconstructed the history of arroyo evolution by combining trench data with arroyo-scale information from aerial imagery, light detection and ranging (LiDAR), longitudinal profiles, and repeat surveys of cross sections. Burial signatures in annual rings of salt cedar and willow dated sedimentary beds greater than 30 cm thick with annual precision. Along both arroyos, incision occurred until the 1930s in association with extreme high flows, and subsequent filling involved vegetation development, channel narrowing, increased sinuosity, and finally vertical aggradation. A strongly depositional sediment transport regime interacted with floodplain shrubs to produce a characteristic narrow, trapezoidal channel. The 55 km study reach along the Rio Puerco demonstrated upstream progression of arroyo widening and filling, but not of arroyo incision, channel narrowing, or floodplain vegetation development. We conclude that the occurrence of upstream progression within large basins like the Rio Puerco makes precise synchrony across basins impossible. Arroyo wall retreat is now mostly limited to locations where meanders impinge on the arroyo wall, forming hairpin bends, for which entry to and exit from the wall are stationary. Average annual sediment storage within the Rio Puerco study reach between 1955 and 2005 was 4.8 × 10^5 t/yr, 16% of the average annual suspended sediment yield, and 24% of the long-term bedrock denudation rate. At this rate, the arroyo would fill in 310 yr.

[†]E-mail: friedmanj@usgs.gov.

INTRODUCTION

Background

The dynamics of riverine erosion and sediment transport are a central focus of fluvial geomorphology, but they are difficult to address because they are episodic, spatially complex, far from steady state, and strongly scale dependent (Knox, 1977; Hereford, 1984; Balling and Wells, 1990; Trimble, 1999). Identifying the events and processes that control these sediment dynamics requires precise measurements, but overcoming spatial and temporal variability requires observations over large distances and long times. Addressing this challenge, therefore, requires integration of data collection efforts at point, cross-section, reach, and whole-river scales. The present paper applies such a multiscale approach to investigate the process of arroyo filling along two ephemeral streams in the southwestern United States.

Arroyos

Arroyos are deep, oversized channels usually with vertical or steeply cut walls of silt, clay, or sand (Dodge, 1902; Schumm and Hadley, 1957; Cooke and Reeves, 1976; Gellis et al., 2012). They occur in semiarid or arid regions worldwide (Prosser et al., 2001; Sancho et al., 2008; Mehl and Zárate, 2012; Boardman, 2014). Arroyo systems are inherently unstable, shifting at the century to millennial scale between an unincised aggradational state, in which floods are attenuated across a broad floodplain, and an incised state, in which floods, trapped within an oversized rectangular channel, have a higher unit stream power and are capable of net erosion.

Three distinct phases of the arroyo cycle can be recognized, an unincised phase, arroyo cutting, and arroyo filling. This progression is driven by both autogenic processes (Schumm and Hadley, 1957; Elliott et al., 1999), and external stimuli, including intense precipitation (Hereford, 1984), human influences such as livestock grazing and channel modification (Thornthwaite et al., 1942; Love, 1997; Boardman, 2014), and climate change (Karlstrom and Karlstrom, 1987; Harvey and Pederson, 2011). In the unincised phase, a narrow channel migrates across a broad floodplain, and the sediment supply is greater than or equal to the capacity of the stream to transport sediment. Incision (Fig. 1) is initiated when the transport capacity, represented here by the channel-average boundary shear stress, is increased relative to the load. This may result from (1) an increase in slope caused by base-level lowering (Schumm and Parker, 1973) or channel straightening (Simon, 1989), (2) an increase in runoff caused by intense rainfall or any factor that decreases upland vegetation cover, including drought or livestock grazing (Bryan, 1925; Osterkamp and Friedman, 2000; Prosser et al., 2001; Mehl and Zárate, 2012), (3) artificial channelization of the flow (Cooke and Reeves, 1976), (4) removal of vegetation on the channel boundary (Thornthwaite et al., 1942; Tucker et al., 2006), or (5) a decrease in the rate of sediment supply from upstream (Schumm and Hadley, 1957). After the flow is confined within the nascent arroyo, flow depth and shear stress during high flows are increased, resulting in further incision. As the arroyo deepens, the walls become more susceptible to collapse (Simon and Collison, 2002), leading to further erosion by arroyo widening as the sediment formerly in the arroyo wall is transported downstream (Elliott et al., 1999; Fig. 1).

As the arroyo widens, flow depth at a given discharge decreases, reducing shear stress during high flows. As a result, there is a shift from arroyo cutting to filling: Sediment deposition begins to occur within the arroyo, vegetation becomes established on the arroyo floor, and channel narrowing and floodplain formation occur (Schumm and Hadley, 1957; Gellis et al., 2012; Fig. 1). In the arroyo filling phase, arroyo widening continues slowly while arroyo depth decreases through deposition. Deposition

GSA Bulletin; March/April 2015; v. 127; no. 3/4; p. 621–640; doi: 10.1130/B31046.1; 15 figures; 2 plates; 2 tables; Data Repository item 2014320; published online 16 September 2014.

For permission to copy, contact editing@geosociety.org
© 2014 Geological Society of America

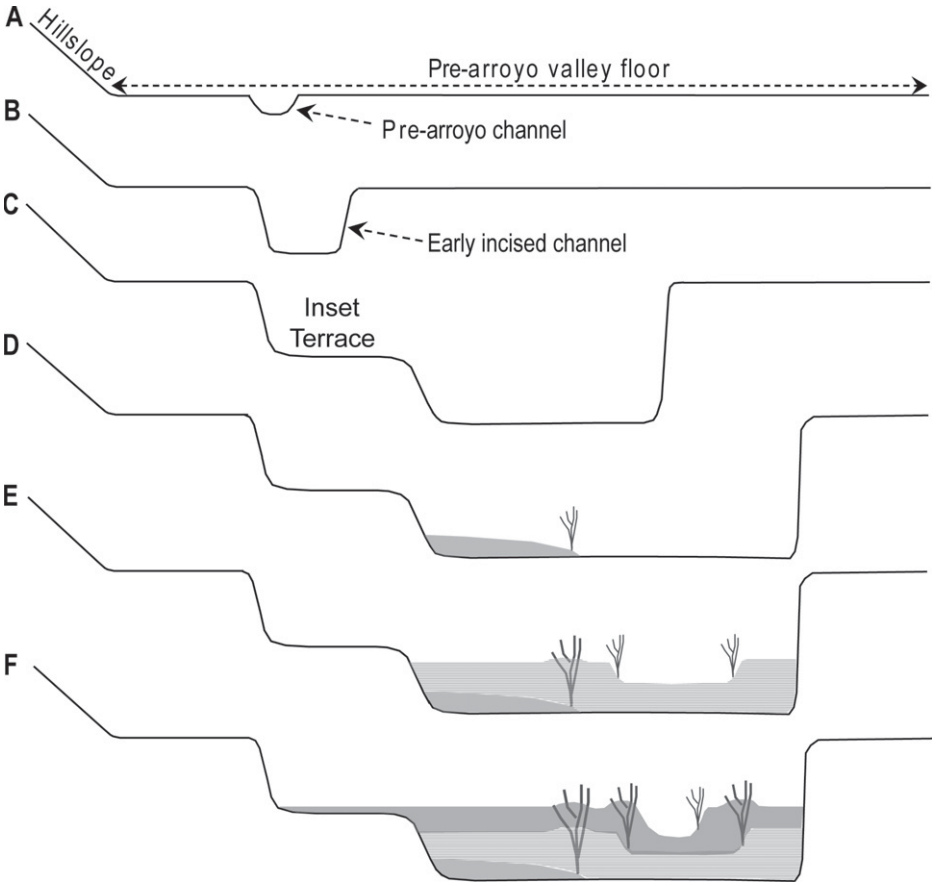


Figure 1. The arroyo cycle at a cross section. (A) The unincised phase in which the floodplain is at the level of the valley floor. (B) Channel incision and widening. (C) Further incision and widening, and migration of the erosional channel to the right leaving an inset (cut) terrace. (D) Beginning of arroyo filling and channel narrowing, continuation of arroyo widening at a reduced rate, and establishment of a salt cedar or willow just above the channel bed. (E) Continued channel narrowing, aggradation of channel and floodplain, sediment deposition around salt cedar forming a channel levee, and establishment of two more salt cedars adjacent to the channel. (F) Continued aggradation and migration of the channel, burial of the inset terrace, formation of new levees, and establishment of another salt cedar. Shaded areas indicate sediment deposition between illustrations.

within the arroyo is enhanced by increasing channel sinuosity, increasing vegetation density, and increasing arroyo width, all of which decrease shear stress along the channel bed and floodplain. The arroyo may completely fill or re-incise because of a change in flood intensity or sediment supply (Love, 1986).

Arroyo incision locally increases slope, leading to upstream propagation of a wave of incision (Bull, 1997). Waves of incision may be followed by upstream propagating waves of deposition as a result of local widening and transport of sediment from incising reaches upstream (Schumm and Hadley, 1957; Gellis et al., 2012). Experimental studies have sometimes shown that the wave of deposition is followed by re-incision as the sediment source becomes more remote ("complex response" of Schumm and Parker, 1973). Along rivers, time transgression may be overwhelmed by factors such as bedrock control, tributary influence, agricultural activities, and groundwater availability (Karlstrom and Karlstrom, 1987; Hereford, 2002), and most arroyo studies have examined too short a reach in insufficient detail to observe whether time transgression actually occurs.

The arroyo cycle recurs on a millennial scale (Mann and Meltzer, 2007). Although spatial autocorrelation of these drivers can cause partial synchrony of arroyo activity across a region (Waters and Haynes, 2001; Mann and Meltzer, 2007), spatial variation in weather, and differences in response times among arroyos prevent perfect synchrony (Graf, 1980; Elliott et al., 1999). In the southwestern United States, the most recent widespread incision began around 1880 (Bryan, 1925).

Arroyo research has historically been hindered by limited temporal precision of the commonly used radiocarbon dating method, and limited data density and spatial coverage of traditional surveying methods. However, a new dendrochronological method allows dating of stratigraphic units with annual precision (Friedman et al., 2005), and remote-sensing techniques including light detection and ranging (LiDAR) and satellite imagery allow detailed analyses of channel change over large areas (Perignon et al., 2013; Griffin et al., 2014).

Study Sites

Rio Puerco

The Rio Puerco flows ~250 km from the Nacimiento Mountains in north-central New Mexico south to the Rio Grande near Albuquerque (Fig. 2). The watershed is dominated by Mesozoic and Cenozoic sedimentary rocks and occupies 19,040 km^2 (Heath, 1983). In the lower 100 km of the Rio Puerco valley, the late Quaternary sediments deposited by the Rio Puerco and its tributaries are underlain by the Santa Fe Group, a thick unconsolidated accumulation of terrestrial sediments deposited in intermontane basins during the late Oligocene to middle Pleistocene (Heath, 1983). Mean annual precipitation ranges from 212 mm near the mouth to over 400 mm in the mountains (Molnar and Ramirez, 2001). Peak flows in the lower Rio Puerco are typically flash floods caused by late-summer thunderstorms (Heath, 1983; Molnar and Ramirez, 2001). The Rio Puerco carries a heavy load of clay, silt, and sand (Nordin, 1963; Love, 1986); larger particles occur only locally.

The study site extends 55 km along the river valley (87.5 km along the river centerline in 1996) from U.S. Geological Survey streamflow gauging station number 08352500, Rio Puerco at Rio Puerco, located at the crossing of Highway 6, downstream to streamflow gauging station number 08353000, Rio Puerco near Bernardo, New Mexico, 5 km upstream of the confluence with the Rio Grande (Fig. 2). The study site ranges in elevation from 1440 to 1536 m above mean sea level (NAVD88), and the streambed gradient is ~0.001 (Griffin et al., 2005). The slope of the pre-arroyo valley floor is 0.0016. Flow in this reach is intermittent, and in the absence of tributary input, it tends to decrease downstream because of infiltration (Heath, 1983; Griffin et al., 2014).

Floods from the mid-1800s to early 1900s incised a continuous arroyo along the lower 200 km of the Rio Puerco (Fig. 3; Bryan, 1928;

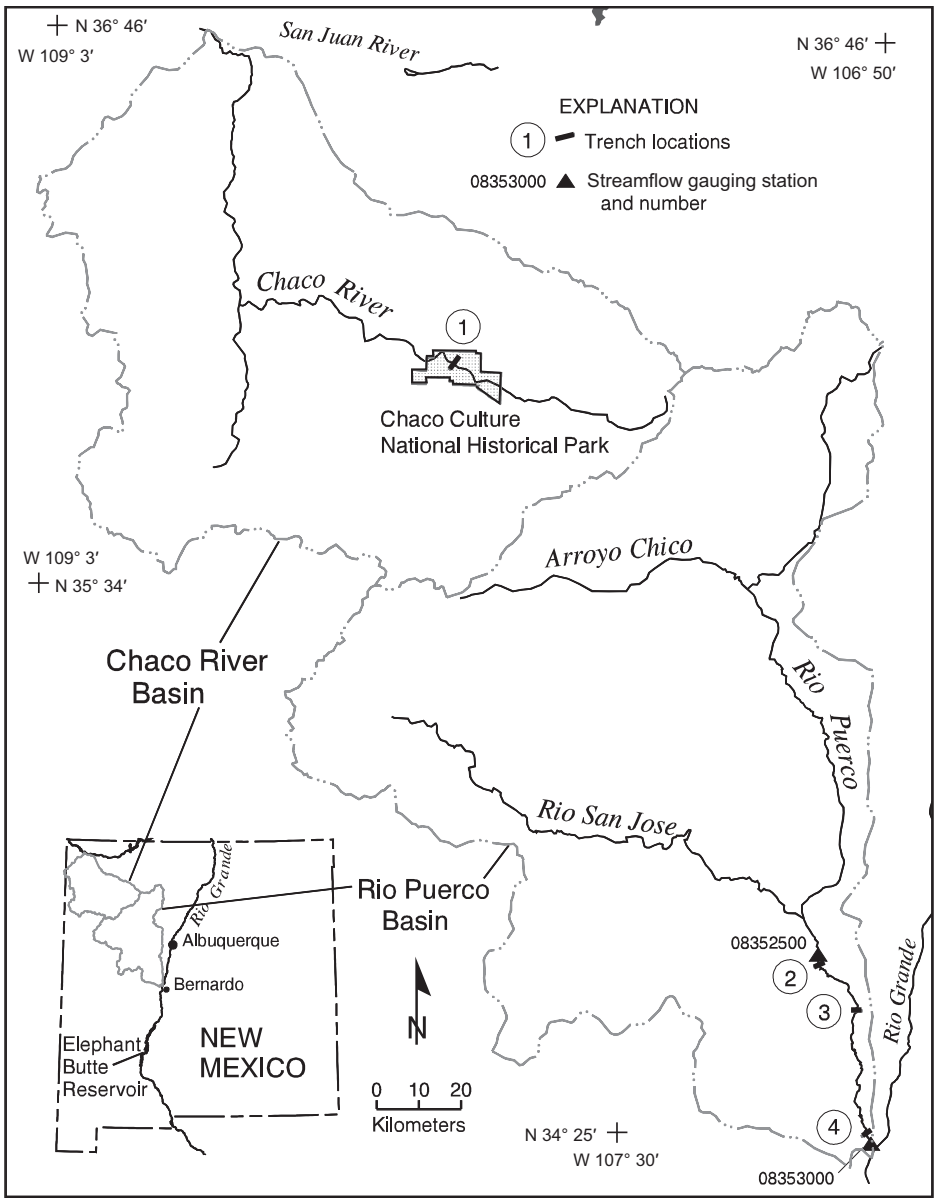


Figure 2. Watersheds of Rio Puerco and Chaco River, New Mexico, and locations of trenches and streamflow gauging stations. The trenches are (1) Chaco, (2) Highway 6, (3) Belen, and (4) Bernardo. Precise trench location information is in Table DR1 (see text footnote 2). The base map is from U.S. Geological Survey Digital Data (1999).

Elliott et al., 1999). Downstream from the confluence with the Rio San Jose (Fig. 2), the period of downcutting ended shortly after the highest known instantaneous discharge, 1070 m^3/s on 23 September 1929 (Fig. 4; New Mexico State Engineer, 1930). In 1935, a braided channel occupied most of the arroyo bottom, and woody vegetation was scarce within the arroyo (Fig. 3; Friedman et al., 2005). Since the 1930s, peak flows have decreased (Fig. 4), the channel downstream of the confluence with the Rio San Jose has narrowed, a densely forested floodplain has developed (Fig. 3), and the arroyo has partly filled (Elliott et al., 1999; Griffin et al., 2005). The floodplain forest is dominated by the Eurasian large shrub salt cedar (genus *Tamarix*, locally introduced in 1926; Bryan and Post, 1927), with a band of sandbar willow (*Salix exigua*) along the channel.

Chaco Wash

Chaco Wash flows west 42 km through northwest New Mexico before joining Escavada Wash to form the Chaco River, a tributary of the San Juan River (Fig. 2). The lower 32 km of Chaco Wash are within a canyon, 500–1000 m wide, cut into Cretaceous Cliff House sandstone and the Menefee Formation (Love, 1980). Average annual precipitation in the Chaco Wash watershed ranges from 252 mm at Star Lake, New Mexico (elevation 2024 m), to 242 mm at Chaco Culture National Historical Park, New Mexico (elevation 1884 m; Western Regional Climate Center, 2012). Maximum elevation is ~2250 m along the continental divide at the southeastern boundary of the watershed, and minimum elevation is 1859 m at the confluence with Escavada Wash. Drainage area upstream from the streamflow gauging station Chaco Wash at Chaco Canyon National Monument, New Mexico (gauge number 09367680), is 1496 km^2. Chaco Wash and Rio Puerco are adjacent drainages (Fig. 2). The study site extends from the New Mexico State Highway 57 bridge crossing near Pueblo Bonito down valley 1.5 km. The trench site is located 950 m down valley along this segment.

Multiple episodes of arroyo cutting and filling are recorded in Chaco Canyon. The history of the most recent episode strongly parallels that of the Rio Puerco. In 1849, Simpson (1850) observed an intermittent channel or succession of pools. Incision began before 1877, when Jackson (1878) reported a channel more than 4 m deep. Photographs and channel measurements beginning in 1896 describe an incising arroyo with little vegetation and a flat bottom until the early 1930s (Love, 1980). In the 1930s, Chaco arroyo had a rectangular cross section similar to that of the Rio Puerco at the same time. The arroyo bottom was occupied by a broad sand-bed channel with no levees and little floodplain or riparian vegetation. Since that time, a floodplain has developed, and the channel has narrowed (Gellis, 2002). The current arroyo bottom is similar to that of the Rio Puerco, and it includes a narrow channel, levees, and a densely vegetated floodplain dominated by salt cedar. As at Rio Puerco, arroyo filling over the last half century is attributed to multiple factors, including climatic fluctuations, decreased grazing, and introduction of salt cedar (Love, 1980). An erosion control program from 1934 to 1952 included fencing to reduce grazing, local construction of revetments to stabilize arroyo walls, and planting of 700,000 trees and shrubs, including salt cedar, mostly in the bottom of the arroyo.

Study Questions

We used a multiscale approach to address seven fundamental issues of arroyo evolution. How do the channel and floodplain of a filling arroyo differ from those of an erosional arroyo or stable system? What are the sedimentological characteristics and facies of arroyo fill deposits, and how do they vary with depositional envi-

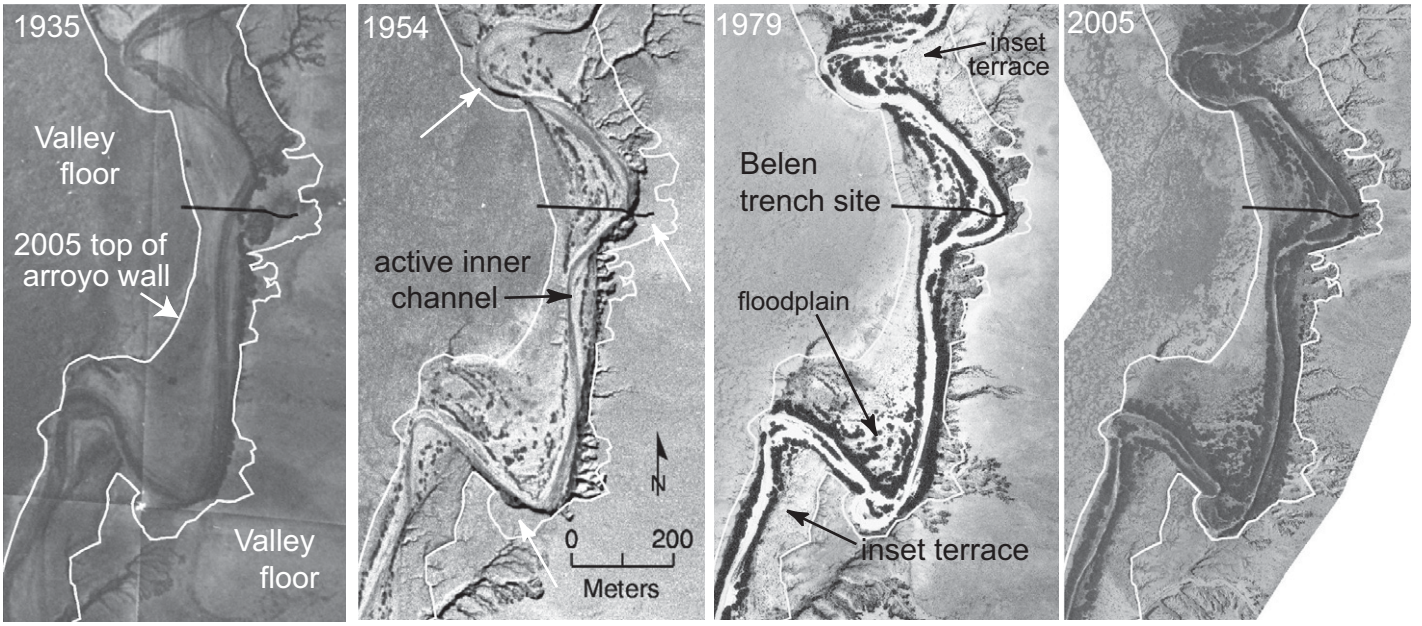


Figure 3. Aerial photographs of a 1.4 km segment of the Rio Puerco including the Belen trench site in 1935, 1954, 1979, and 2005. The white lines are tops of the arroyo walls mapped from 2005 imagery, and the black line indicates the trench location. Only three small areas of canopy are visible in the 1935 image, covering less than 1% of the arroyo bottom. Shrub canopy coverage of the arroyo bottom increased to 17.2% in 1954, 44.1% in 1979, and 63.1% by 2005. Average arroyo width increased from 187 m in 1935 to 218 m in 2005 as a result of erosion of valley fill at the sites indicated by the white arrows.

ronment? What kinds of fluvial events produce arroyo fill deposits, and what are their return intervals? To what extent is the process of arroyo filling time transgressive? What are the rates of arroyo filling at the event, decadal, and century time scales? How do processes of arroyo widening differ between cutting and filling arroyos? How does vegetation influence channel form, flood attenuation, and sediment deposition in a filling arroyo?

METHODS

Multiscale Approach

We precisely dated the stratigraphy at points on the floodplain using a new method based on the burial signatures in tree rings (Friedman et al., 2005). We scaled up to cross sections using trench stratigraphy, and we interpolated between trenches using LiDAR digital terrain models (DTMs), a rectified sequence of aerial images, measured longitudinal profiles, repeat surveys of cross sections, and published historic observations and measurements of the arroyo.

Tree Scale

Using a backhoe and hand tools, we excavated salt cedars and sandbar willows adjacent to four trenches (see following). We used present topography, apparent tree age, and the sequence of aerial photographs to select the smallest set of trees that would date all important deposition events (4–10 trees per trench; total of 29 trees). Tree excavations extended down to the apparent establishment surface or to the maximum depth of safe excavation (3–5 m). We harvested up to four buried stems (mean = 2) from each tree to reduce error resulting from rot or inconclusive burial signatures in individual stems. We used aluminum nails driven into the stems to mark stratigraphic contacts. After harvesting, we cut a slab at each stratigraphic contact using a bandsaw. The upper surface of each slab was 1 cm above the contact. Additional slabs were cut to aid in cross-dating (the matching of annual rings between slabs; Stokes and Smiley, 1968). To prepare slabs for tree-ring analysis, we sanded them with progressively finer sandpapers to a median particle size of 15 μm (600 grit).

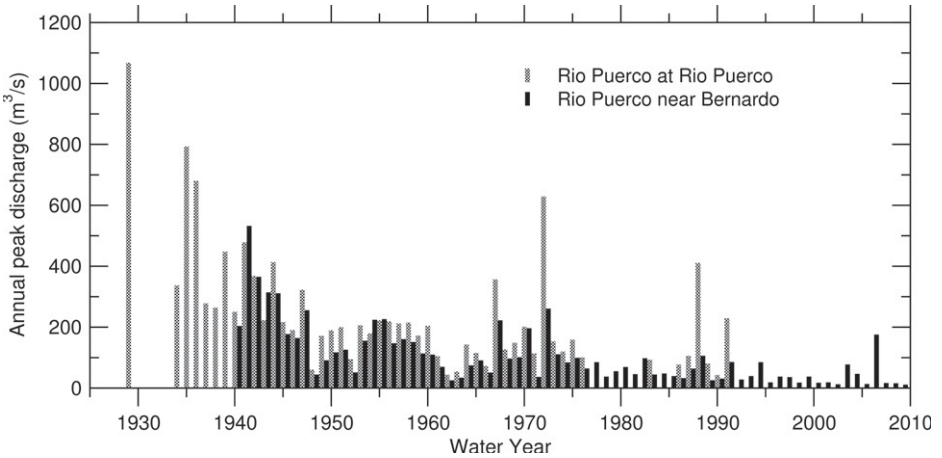


Figure 4. Annual peak instantaneous discharge at U.S. Geological Survey streamflow gauging stations Rio Puerco at Rio Puerco (gauge no. 08352500) and Rio Puerco near Bernardo, New Mexico (gauge no. 08353000). Gauge locations are shown in Figure 2.

We digitized ring width and year on a Velmex TA Unislide measuring system with ACU-Rite linear encoder and QC1100 digital readout device acquired from Velmex, Inc. (Bloomfield, New York). We recorded ring widths with Measure J2X, version 3.1 (rel. 25), software from Project J2X, Voortech Consulting (Holderness, New Hampshire).

We determined the year of deposition of stratigraphic units through identification of burial signatures in the tree rings. When a stem is buried, subsequent annual rings in the buried section develop characteristics of roots (Sigafoos, 1964; Nanson and Beach, 1977). In salt cedar and sandbar willow, rings in buried stems become narrower, vessels within the rings become larger, and transitions between rings become less distinct (Friedman et al., 2005; Dean et al., 2011). Finally, for each stem, we determined the year and elevation of the establishment point—the point below which there is no pith, and the entire cross section is root (Friedman et al., 2005).

Trench Scale

Between 1999 and 2001, we used a backhoe to dig trenches 1.8 m deep across the floodplain at Chaco Wash in Chaco Culture National Historical Park, New Mexico, and at three locations along the Rio Puerco, New Mexico, near Highway 6, Belen, and Bernardo (Fig. 2; Plate 1[1]; Table DR1[2]). To obtain as complete a sedimentary record as possible, we located trenches at sites where the thalweg had migrated only once across the arroyo bottom over the 65 yr of channel narrowing. The trenches at Chaco Wash, Highway 6, and Belen spanned the entire arroyo. The trench at Bernardo, however, extended only from the east arroyo wall to the channel at the time of survey (about half of the arroyo width); the incised channel made the west half of the arroyo inaccessible at this site. We used a self-leveling engineer's level and surveyor's rod to install horizontal strings on the trench face as vertical control, and we used surveyor's tapes to obtain horizontal distances, allowing us to determine the precise (±1.0 cm) locations of contacts on a stratigraphic log. We cleaned the trench face with trowels and brushes, and we noted sedimentary textures, structures, and facies on the log.

[1]Plates 1 and 2 are on a separate sheet accompanying this issue.

[2]GSA Data Repository item 2014320, supplementary information including precise trench locations, spatial and temporal coverage of aerial imagery, accuracy of image registration and rectification, registration of arroyo width and depth data and calculation of changes in arroyo volume, is available at http://www.geosociety.org/pubs/ft2014.htm or by request to editing@geosociety.org.

Arroyo Scale

Rio Puerco

Data sources. At Rio Puerco, we analyzed spatial and temporal variation of arroyo-scale geomorphic features within the study reach using aerial imagery from 1935, the 1950s, the 1970s, and 2005; high-precision real-time kinematic global positioning system (GPS) surveys of arroyo cross sections and longitudinal profile from 2002, 2007, and 2010; DTMs derived from a 2005 aerial LiDAR survey; historical measurements of arroyo dimensions in 1855, 1898, 1927 (Bryan and Post, 1927; Bryan, 1928), and 1936 (Elliott et al., 1999); and rod-and-level surveys of 39 channel cross sections in 2002 (Griffin et al., 2005). Details of spatial and temporal coverage and registration are provided in Tables DR2 and DR3 (see footnote 2). All data are in the UTM coordinate system, Zone 13, referenced to the horizontal North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88). Arroyo features and measurement conventions are defined in Figure DR1 (see footnote 2).

Arroyo width. Mapped features included arroyo top width, arroyo bottom width, and the arroyo centerline, which provides the down-valley distance in valley kilometers (vk) from the concrete sill at the Highway 6 crossing. The arroyo bottom includes the channel and floodplain but excludes areas within the arroyo that are not flooded in the current flow regime, such as inset terraces, arroyo walls, and tributary fans. Using a geographic information system (GIS), we measured arroyo top and bottom areas in 1935, 1950s, 1970s, and 2005 images for 0.5 km intervals along the valley centerline. This interval length captured the large and unsystematic variability in arroyo width. We divided arroyo top and bottom area for each interval by 500 m to determine the mean arroyo top and bottom widths. Arroyo top width in 1927 was derived from Bryan and Post (1927) and registered to our coordinate system as described in the Data Repository (see footnote 2).

Arroyo volume and depth. We calculated changes in arroyo volume over time in the 0.5 km valley intervals relative to the volume in 2005 as determined from the LiDAR DTMs. Because of complex arroyo topography and limitations in the lateral extent of the DTMs, it was not possible to define a series of planar segments demarcating the top of the arroyo and intersecting the DTMs in all areas. Instead, we used the DTMs to define 42 arroyo cross sections along the study reach and calculated mean depth at each cross section as area divided by top width. Variability in average arroyo depth is small and systematic in the down-valley direction. Cross-section locations were selected to capture the trends and limits (minimums and maximums) of arroyo depth. We interpolated between cross sections to determine average depth in each 0.5 km valley interval and multiplied average depth by the planimetric area of the interval mapped from imagery to obtain estimates of volume in 2005. We estimated arroyo volumes in earlier years for each 0.5 km interval by calculating changes relative to 2005 in depth and in planimetric top and bottom areas as described in the Data Repository (see footnote 2).

Channel width, shrub cover, and sinuosity. We mapped edges of the channel and shrub canopy coverage from registered and rectified aerial photographs acquired in 1935, the 1950s, 1970s, and 1996 as described by Griffin et al. (2014). We carried out computations of shrub canopy cover and average channel width in five subreaches covering a total of 8.62 vk, or 15.7% of the study reach. Subreach lengths ranged from 1.50 to 2.18 vk, with an average length of 1.72 vk. We calculated the average fraction of the arroyo bottom (floodplain plus channel) covered by shrub canopy (Griffin et al., 2014). Accuracy was estimated to be within 5%. We computed average channel sinuosity in 1935, 1950s, 1970s, and 2005 from mapped channel and arroyo centerlines.

Sediment discharge. Sediment available for transport within the Rio Puerco arroyo is almost entirely fine to very fine sand, silt, and clay, and the dominant mode of transport is as suspended load. Nordin (1963), Elliott et al. (1999), and Bierman et al. (2005) showed that large quantities of sand and finer material are moved through the arroyo as suspended load, and Nordin (1963) and Griffin et al. (2014) showed that grain sizes as large as 0.5 mm (medium sand) are transported in suspension in flows as shallow as 1 m. Sediment in suspension moves with the velocity of the fluid, whereas sediment transported as bed load moves only intermittently and at small velocities in the near-bed region of the flow. High concentrations of sand in suspension have been recorded at the streamflow gauging station Rio Puerco near Bernardo, New Mexico (U.S. Geological Survey, 2012; Nordin, 1963). Griffin et al. (2014) determined that the samples containing the highest total suspended sediment concentrations (>199,000 mg/L; n = 59) all contained sand. The average concentration of sand in these samples was 59,600 mg/L, and the sand fraction was an average of 23% of the samples. Although some sand is transported as bed load within this system, almost all of the silt and clay and the majority of sand are transported through the arroyo in suspension (Griffin et al., 2014). Therefore, we assumed that bed load is negligible in calculations of sediment transport.

We determined annual sediment discharge from the Rio Puerco using daily mean sediment discharge for the period 1 October 1955–30 September 2005 obtained from the National Water Information System Water-Quality Data (U.S. Geological Survey, 2012) for the streamflow gauging station Rio Puerco near Bernardo, New Mexico. We compared suspended sediment loads to changes in arroyo volume assuming a density of 2650 kg/m^3 and a porosity of arroyo-wall sediment of 0.35.

Chaco Wash

The National Park Service (1934) carried out a detailed topographic survey of the study area from 1931 to 1933. We merged the individual map sheets into a single image registered to the UTM coordinate system using common data points obtained from a high-precision GPS survey conducted in 2000. We shifted elevations to match the NAVD 88 datum by adding 8.00 m. This vertical shift was determined by comparing elevations at known, fixed points. The 1930s map included a line identifying the location of the channel thalweg through the study reach. The lack of a long-term stream gauge at Chaco makes it difficult to identify flow events responsible for specific episodes of deposition or erosion at that site. The streamflow gauging station Chaco Wash at Chaco Canyon National Monument, New Mexico (gauge number 09367680), was active only from 8 April 1976 through 10 May 1990.

The 2000 GPS survey included the ground surface along the trench cross section, a longitudinal profile of the channel thalweg, and tops of the north and south arroyo walls through the study reach. We used the surveyed points to create linear features in a GIS. The arroyo centerline served as a common distance reference through time. We measured arroyo top width in 2000 between the lines identifying the tops of the arroyo walls at points spaced 20 m apart along the arroyo centerline. We mapped tops of the arroyo walls in the 1930s from the 1 ft (0.3 m) contours and break lines on the National Park Service (1934) map, and we determined arroyo width at 20 m intervals in a similar manner.

We also estimated channel top width in the 1930s from the 1 ft (0.3 m) elevation contours relative to the location of the channel thalweg shown on the map. We estimated bankfull depth in the 1930s as being ~1.2 m and interpolated between contours to identify the edge of the channel where the break in slope was not obvious. We computed channel width as a function of distance along the arroyo centerline from the mapped edges of the channel. We determined longitudinal profiles of thalweg elevation as a function of distance along the arroyo centerline from 98 thalweg points in the 2000 GPS survey and 10 elevation contour crossings in the 1930s map data.

RESULTS

Tree Scale: Local Erosion and Deposition Quantified from Tree Rings

The dating results from individual trees (Fig. 5A) are highly precise. Beds in rapidly aggrading locations, such as channel levees or lateral bars within narrowing channels, could often be attributed to a single flood event on the basis of stratigraphy and multiple consistent dates from different stems. Such beds are depicted as vertical line segments on Figure 5A. Deposits in more slowly aggrading environments, such as floodplain depressions, consisted of interbedded layers, each millimeters to centimeters in thickness, deposited by multiple events over many years. For these deposits, only the time period over which the multiple events occurred could be documented with confidence, and such beds are depicted on Figure 5A as diagonal line segments. Time periods when no sediment deposition occurred, lasting from 1 yr to a decade or more, are depicted in Figure 5A as horizontal line segments. For clarity, we show here deposition at only 3 of 9 trees from the Belen trench.

At the Belen trench, identifiable sedimentary units were deposited in 1941, 1945, 1953, 1955, 1957, 1967, 1972, 1985, 1986, 1988, 1991, 1994, 1997, and 1999 (Fig. 5A). These depositional events correspond with high-flow events in the hydrologic record (Fig. 4), demonstrating the ability of this method to date beds thicker than ~30 cm with annual precision. Discharge necessary to overtop the levee at the trench location in 2002 was ~35 m^3/s. In many cases (e.g., 1967), a stack of beds all date to the same year (Plate 2 [see footnote 1]), indicating a flood with multiple peaks or deposition by a sequence of sand waves during a single high flow. The timing, amount, and character of sediment deposition varied greatly from one tree to another within a cross section (example from the Belen trench; Fig. 5A; Plates 1 and 2 [see footnote 1]). At horizontal distance (HD) = 39 m, far from the channel and close to the arroyo wall, deposition was most rapid in the 1940s and 1950s, and elevation approached the modern level in the 1967 flood. At HD = 105 m, closer to the channel, deposition was most rapid in the 1950s and 1960s and approached the modern level in the 1972 flood. At HD = 167 m, on the present-day levee, deposition occurred in the 1980s and 1990s. At all trees, the thickest sedimentary units consisted of very fine sand deposited during channel narrowing and levee construction. Most deposition of silt and clay within the arroyo was relatively recent and occurred as thin sheets in low-velocity back-water areas of the floodplain distal to the channel levee (Plates 1 and 2 [see footnote 1]).

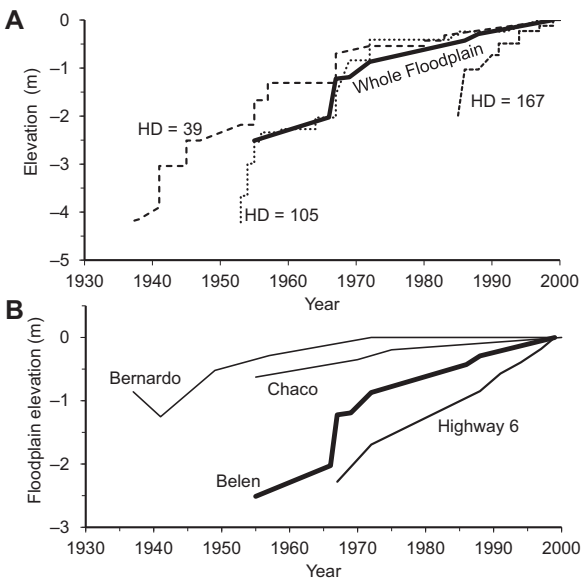


Figure 5. Variation in sediment accumulation among trees and trenches. (A) Sediment accumulation rates at three trees and for the whole floodplain, Belen trench, Rio Puerco, New Mexico. Datum is the ground surface at the time of excavation. Tree locations are given as horizontal distance (HD) in meters along the trench (Plate 2 [see text footnote 1]). (B) Whole floodplain sediment accumulation rates at four trenches, Rio Puerco and Chaco Wash, New Mexico. Datum is the average floodplain elevation at the time of excavation.

Trench Scale

Trench Stratigraphy

Sediment transported by the Rio Puerco and Chaco Wash and revealed in all four trench exposures (Plate 1 [see footnote 1]) consisted almost entirely of sand, silt, and clay; coarser particles were rare, but the trench exposures also included a few armored clay balls (Nordin and

Curtis, 1962), e.g., at Chaco HD = 15 m and Bernardo HD = 178 m. Away from the trenches, we observed sparse, local lag deposits of gravel on the bed, especially downstream from tributary junctions. In the modern arroyo, sediments deposited by a single overbank flood event showed facies trending from sand in the high-velocity environment of the channel margin and levee tops, to silt on levee margins, and then to clay in the low-velocity environment of floodplain depressions beyond the levee. Because of variation in provenance and organic matter input, beds often had distinctive coloration useful in stratigraphic mapping, including buff, red, pink, brown, tan, green, purple, and black (Plate 1 [see footnote 1]).

Bedding in all four trench faces showed fining-upward sequences at the scale of the entire cross section and at the event scale (Plate 1 [see footnote 1]). At the scale of the entire cross section, sand was especially abundant at the base of the arroyo fill, because at the beginning of the period of aggradation the channel was wide, levees and floodplain were poorly developed, and low-velocity environments suitable for deposition of silt and clay were uncommon. As the channel narrowed and floodplain and levees developed, low-velocity areas on the floodplain became extensive, resulting in broad thin deposits of silt and clay. Recent deposits near the channel at Highway 6 contained more sand than such deposits at the downstream trenches because Highway 6 is closer to the upstream source of sediment and because sand settles more rapidly than silt or clay.

At the event scale, many sand beds were capped by thin (i.e., 1–2 cm) silt or clay lamina deposited during declining flows. While working along the channel, we observed analogous thin silt deposits forming on the channel bed as flows declined. Sediments dating to a single year commonly consisted of multiple beds fining upward from sand to clay as a result of multiple discharge peaks and temporal fluctuations in sediment load at the scale of minutes to hours. Silt or clay layers exposed at the ground surface for many years were commonly darkened with organic matter and included leaf fragments (e.g., thin beds at Chaco HD = 5–14 m and at Highway 6 HD = 60–64 m; Plate 1 [see footnote 1]). Although most beds showed little evidence of erosion, erosional contacts were found in predictable locations, including at the arroyo margin, in the channel bed and banks, and in cut-and-fill sequences recording temporary widening and subsequent narrowing (e.g., at Belen HD = 157 m and Bernardo HD = 58 m; Plate 1 [see footnote 1]). Beyond the erosional contact defining the maximum arroyo extent, there were nearly planar beds of clay, silt, and sand apparently deposited by overbank flows on the broad floodplain prior to incision of the arroyo (e.g., Highway 6 HD = 0–3 m; Plate 1 [see footnote 1]). Outside of the trenches, the arroyo walls locally contained evidence of past arroyo fills more similar to the fill of the modern arroyo.

Sedimentary structures were mostly lamina parallel to the bed surface. Cross-bedded sands were less common, except in climbing ripples on levee crests. Although the trench exposures were dominated by fluvial deposits, we also observed windblown sand, especially in falling dunes deposited against the arroyo wall, (e.g., at Belen HD = 1–22 m; Plate 1 [see footnote 1]). Poorly sorted colluvium, including blocks resulting from failure of the arroyo wall, commonly interfingered with fluvial sediments at the margin of the arroyo bottom.

Trench-Scale Erosion and Deposition Dated by Linking Tree-Ring Dates to Stratigraphy

Because of the large variation among trees in timing and rate of sediment deposition, it would be imprecise to determine cross-section-averaged sediment deposition rates from these point measures alone. The trenches improve such determinations by quantifying the variation in thickness of each unit along the cross section and by showing the locations of erosional contacts. Documenting the chronostratigraphy of the whole trench cross section (Plate 2 [see footnote 1]) required interpolating between trees (Fig. 5) on the basis of stratigraphy (Plate 1 [see footnote 1]). Some portions of the cross section were more precisely dated than others. Therefore, developing a chronostratigraphic mapping scheme that was valid for the entire cross section required a decrease in temporal resolution (Plate 2 [see footnote 1]) compared to the data from individual trees (Fig. 5A). Chronostratigraphic units on Plate 2 (see footnote 1) typically span 5 or 10 yr.

In addition to recording local rates of sediment deposition through burial signatures within tree rings, salt cedars can also record past thalweg elevation in their establishment age and elevation. Because of the high seedling requirement for water, salt cedar establishment usually occurs on channel bars. Along the present channel, such establishment surfaces are less than 1 m above the thalweg. Along the Bernardo trench, all eight of the salt cedars for which the establishment point was excavated (Table 1) germinated between 1936 and 1943 on the channel bed, as indicated by trench sedimentology and

TABLE 1. ESTABLISHMENT YEARS AND ELEVATIONS OF EXCAVATED TREES

Trench	Year	Horizontal distance (m)	Elevation (m)	Height above modern thalweg (m)
Chaco				
	1944	6	2.98	1.01
	1969	37	2.33	0.36
	<1954	55	<3.53*	<1.56
	1949	67	2.38	0.41
Highway 6				
	<1971	12	<1.43*	<–2.05
	<1983	33	<3.50*	<0.02
	<1964 or 1965	46	<1.40*	<–2.08
	<1967	58	<2.69*	<–0.79
	1946	88	3.34	–0.14
	1936	103	2.68	–0.80
Belen				
	1991	13	4.77	2.25
	1937	39	0.44	–2.08
	<1979	57	<3.12*	<0.60
	<1954	83	<1.86*	<–0.66
	<1951	105	<0.76*	<–1.76
	1961	154	2.02	–0.50
	<1983	164	<3.76*	<1.24
	<1982	167	<3.43*	<0.91
	<1968	182	<3.58*	<1.06
Bernardo				
	<1956	24	<3.95*	<3.30
	1942	33	3.45	2.80
	1942 or 1943	33	3.45	2.80
	1941	39	3.50	2.85
	1941 or 1942	39	3.50	2.85
	1938	57	3.95	3.30
	1936–1938	62	4.35	3.70
	1937–1939	63	4.35	3.70
	1936 or 1937	84	4.05	3.40

Note: Trees are ordered by horizontal distance along the trench (HD in meters, Plate 2 [see text footnote 1]). Elevation is relative to the arbitrary datum of Plates 1 and 2 (see text footnote 1). Modern thalweg elevation is the elevation of the thalweg at the time of trench excavation (Plates 1 and 2 [see text footnote 1]). Asterisks mark trees for which establishment point was unobserved because it was below the bottom of the excavation; for these trees, the year and elevation are maximum estimates.

stratigraphy (Plates 1 and 2 [see footnote 1]) and by the 1935 aerial image. These trees can be used to determine past changes in approximate thalweg elevation (Fig. 1). Less commonly, salt cedar becomes established on the floodplain in clay-lined depressions (e.g., Highway 6 trees at HD = 88 m and 103 m; Table 1; Plates 1 and 2 [see footnote 1]). Because they were established so high in the cross section, these trees are less useful for reconstructing past thalweg elevation. Stratigraphy, sedimentology, and past images must be used to determine whether or not the trees were established along the channel.

Highway 6. The Highway 6 site experienced more rapid aggradation in recent decades than the other three trenches. Therefore, the oldest sediments exposed at the base of this trench generally date back only to the 1960s (Plate 2 [see footnote 1]; Fig. 5B). The only older deposits are located at the edge of the floodplain at HD = 104 m and in the inset terrace from HD = 106–150 m (Plate 2 [see footnote 1]). Although sediments older than the 1960s are not visible beneath the current floodplain, their thickness is limited by the fact that a nearby repeat cross section at vk 0.8 showed only a 75 cm increase in elevation of the thalweg between 1936 and 1972 (Elliott et al., 1999).

The dominant process of sediment deposition before the 1980s at Highway 6 was channel narrowing, beginning with deposition of sand in lateral bars, especially within bands of salt cedar at the channel margin. Each lateral bar rose in elevation until it became a levee adjacent to the channel and higher in elevation than the rest of the floodplain (Fig. 1; Plate 2 [see footnote 1]). Progressive channel narrowing produced a series of former levees, each higher in elevation than the last. Most levee growth occurred during floods in 1964–1965, 1967, 1969, and 1972 (Fig. 5B; Plate 2 [see footnote 1]). After construction of low lateral bars by moderate flows in 1980–1983, the channel width was approaching the current state. Beginning in 1986, the entire cross section began to aggrade. The channel rose in elevation without shifting laterally while narrowing slightly. Most of the deposition observed in the trench occurred in high flows in 1986, 1988, 1991, 1994, 1996, 1997, and 1999 (Plate 2 [see footnote 1]; Fig. 5B). In spite of the change in depositional mode from channel narrowing to aggradation of channel and floodplain, the average rate of rise in elevation was fairly constant over time, with a quiescent period during a time of low peak flows from 1973 to 1979 (Figs. 4 and 5B). The mean aggradation rate from 1963 to 1999 was 9.1 cm/yr.

The Highway 6 trench gives a relatively complete record of channel aggradation, because throughout the period recorded in the trench stratigraphy (1964–1999), no major channel widening events occurred, and the channel did not migrate laterally. Aerial photos and satellite imagery indicate that arroyo width at this site increased less than 10% (~21 m) by migration of the channel into the west arroyo wall between 1935 and about the 1950s. Arroyo bottom width also changed little between 1935 and 2005 (Table 2). The width of the east-side terrace along the trench path (but east of the trench itself; Plate 1 [see footnote 1]) is ~120 m (43% of top width along the trench path). Average east-side floodplain elevation in 2005 was 1525.8 m, 2.9 m below the average terrace surface elevation, 1528.7 m. At the Highway 6 trench site, arroyo cross-sectional area has decreased from ~2490 m^2 in 1962 to 2180 m^2 in 2002, a 12.4% decrease.

Belen. Most sediment deposition occurred earlier at the Belen trench than at Highway 6. At Belen, channel narrowing occurred in the 1950s (Fig. 3; Plate 2 [see footnote 1]), and the period of most rapid sedimentation was the 1950s and 1960s (average rate of 14 cm/yr from 1954 through 1969; Fig. 5A). After the 1960s, the sedimentation rate was moderate (4.6 cm/yr from 1969 through 1999) and steady (Fig. 5B). Aggradation of the thalweg over time was also less at Belen than at Highway 6. The increase in thalweg elevation from the mid-1930s to 2002 was 3.9 m at Highway 6, but only 2.6 m at Belen. The Belen estimate is based on the establishment elevation of a salt cedar that germinated on the channel bank in 1937 (at HD = 39 m; Plate 2 [see footnote 1]; Table 1) and an estimated bank height of 1 m above the thalweg based on early cross-section measurements of Nordin (1963).

The Belen channel migrated ~100 m to the east between 1935 and 1979, widening the arroyo from 106 m in 1935 to 212 m by 1979 (Fig. 3; Table 2). As a result, pre-1950s deposits are absent in the eastern part of the trench cross section. The oldest dated deposit was from 1937 or earlier, and sediment aggradation was documented between 1941 and 1945 (Plate 2 [see footnote 1]). During the 1950s through 1966, the sediments consisted of broad sheets of streambed sand, and rows of levees. After 1966, sediments consisted of interbedded silt and clay, with localized sand facies at the rows of salt cedar on the floodplain. Between 1969 and 1973, two episodes of channel erosion occurred, as evidenced by the 1972 deposit that is bounded by near-vertical, channel-bank erosional contacts (at HD = 157 m; Plate 2 [see footnote 1]). The first channel-widening event occurred after deposition of the 1969 sediments, and the second occurred after deposition of the 1972 sediments.

After 1973, the channel narrowed to the characteristic trapezoidal shape and aggraded. Between HD = 157 m and 175 m (Plate 1 [see footnote 1]), the inclination of sandy point bar deposits progressively steepened, and as they approached the angle of repose, the deposits became silty stream-bank deposits. Willow plants rooted in these young deposits facilitated sediment deposition, and a row of large salt cedars on the opposite bank (at HD = 183 m on Plate 2 [see footnote 1]) acted to limit erosion of that bank during the erosion events of 1969–1973.

Channel migration at the Belen trench site resulted in large increases in both arroyo top width (106 m or 100%) and bottom width (101 m or 135%) between 1935 and 2005 (Table 2). The increase in arroyo cross-sectional area caused by arroyo widening was mostly counteracted by arroyo filling. As a result, arroyo cross-sectional area at the Belen trench site increased slightly from ~1448 m^2 in 1935 to 1479 m^2 by 2001, with a net increase in area of 31 m^2 (2.1%) during that period.

Bernardo. While the thalweg was aggrading at Highway 6 and Belen, it was degrading downstream at Bernardo. After incising in the 1880s, the arroyo at Bernardo partially filled in the early 1900s, reaching a maximum thalweg elevation around 1936. Aerial photos in 1935

TABLE 2. ARROYO TOP AND BOTTOM WIDTHS AT TRENCH CROSS SECTIONS ALONG THE RIO PUERCO

		Arroyo width (m)							
	Location*	1935		1950s		1970s		2005	
Trench	(km)	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Highway 6	1.60	259	116	276	122	276	123	276	119
Belen	18.7	106	75	172	141	212	176	212	176
Bernardo	53.9	272	100	272	212	295	212	295	247

Note: 2005 data are from light detection and ranging (LiDAR) digital terrain models (DTMs) and surveyed arroyo cross sections.
*Distance down valley from Highway 6.

show a broad braided channel, part of the bed of which is preserved as a sand deposit dating to 1936 (HD = 63–99 m; Plate 2 [see footnote 1]). Between 1936 and 2002, the thalweg eroded a total of ~4.14 m, from 3.6 m below the valley floor in 1936 to 7.74 m in 2002. Two phases of this erosion are documented: in 1937–1941 and 1961–1975. Between 1937 and 1941, two erosional events occurred, as evidenced by the 1937–1938 deposit (at HD = 58 m on Plate 2 [see footnote 1]), which is bounded by near-vertical, channel-bank erosional contacts ~1.5 m high (Plate 1 [see footnote 1]). A second phase of incision that required a lowering of the Bernardo gauging station datum by 1.13 m occurred between 1961 and 1975, mostly in September 1961, as documented in the station analysis files for the gauge.

Channel degradation at Bernardo is recorded in tree establishment elevations. Salt cedar that germinated on the pre-incision channel bed at Bernardo in 1936–1938 (trees at HD = 62 m, 63 m, and 84 m; Plate 2 [see footnote 1]) had establishment elevations 3.40–3.70 m above the present thalweg, and salt cedars established on the inset surface formed after the first phase of erosion (trees at HD = 33 m and 39 m) had establishment years of 1941–1943 and establishment elevations 2.80–2.85 m above the current thalweg (Table 1). In contrast at Belen, establishment elevations of trees that germinated in 1937 and 1961 (HD = 39 m and 154 m) were 2.08 m and 0.50 m below the modern thalweg, reflecting the aggrading thalweg at that location. At Highway 6, establishment elevations of old salt cedars that germinated near the channel were not observable, because they were below the deepest excavations, but formerly aboveground stems were found buried as much as 2 m below the present thalweg elevation (HD = 12 m and 46 m).

Sediment deposition via channel narrowing and floodplain development occurred between the two phases of thalweg incision at Bernardo. During the period 1942 through 1949, sedimentation was rapid, averaging ~8 cm/yr (Plate 2 [see footnote 1]; Fig. 5B), and deposited sediments were mostly sand with thin layers of silt (Plate 1 [see footnote 1]). During the period from 1949 through 1972, sedimentation rates were moderate, and the observed rates were 3 and 4 cm/yr with two short (2–4 yr) periods of nondeposition (Fig. 5B). A levee had developed by 1949, and subsequent deposits behind this levee were dominated by silt. The second phase of incision produced an oversized channel that persisted at the time of trenching. Depth of the thalweg below the levee in 2002 was 5.05 m at Bernardo, compared to 2.99 m and 2.60 m at Belen and Highway 6, respectively. Between the flood of 1972 and trench excavation in 1999, there were no flows large enough to overtop the levee and deposit sediment on the floodplain (Plate 2 [see footnote 1]). Arroyo top width at the Bernardo trench site increased by ~12% (33 m) between 1935 and the 1970s, and width of the arroyo bottom appears to have increased by ~112% (112 m; Table 2).

Chaco Wash. Because the Chaco Wash arroyo is relatively small, and because changes in thalweg elevation have been moderate, the trench exposed most of the post-1931 deposits (Plate 2 [see footnote 1]). Channel change at Chaco Wash since the 1930s has been similar to that at Belen. The predominant change has been channel narrowing by construction of a floodplain and encroachment of the floodplain and levee toward the channel. The thalweg has also aggraded, but only by 0.51 m (Fig. 6). Much of the sediment deposition and channel narrowing occurred in 1951–1955 (Plate 2 [see footnote 1]). A temporary channel-widening event occurred around 1970, and then narrowing continued from 1971 to 1975 until channel dimensions approached those of the trapezoidal channel documented at the time of trenching. Since 1975, floodplain deposition has slowed, and the deposition has been relatively uniform across the channel banks, levees, and floodplain.

Between 1932 and 1950, the point bar on the right side of the channel aggraded ~0.4 m (Plate 2 [see footnote 1]; HD = 68–87 m). Additional sediment deposited during this period is probably below the trench. Trees were estab-

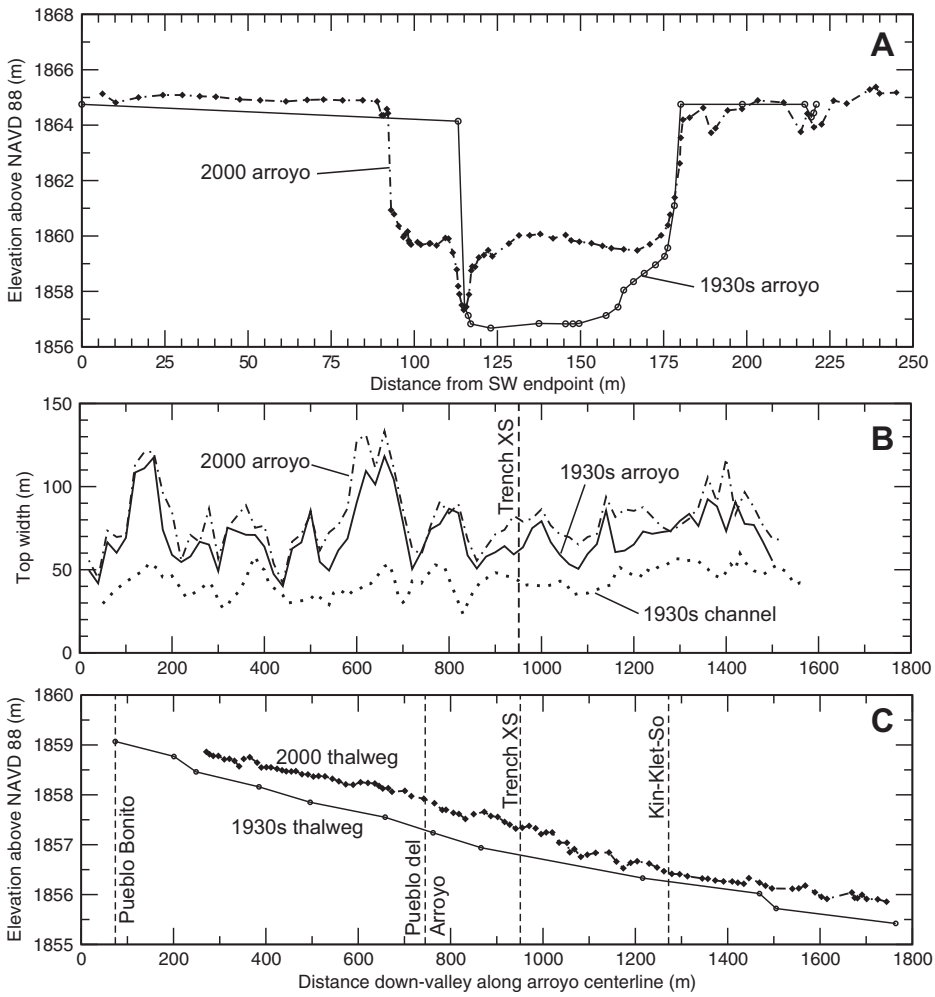


Figure 6. Arroyo geometry in and near the trench at Chaco Wash, New Mexico. (A) Arroyo cross section (XS) at the Chaco trench location in the early 1930s and 2000. The view is looking downstream to the northwest. (B) Arroyo top width at Chaco Wash in the early 1930s and 2000, and channel width in the 1930s as a function of distance down valley along the arroyo centerline. (C) Longitudinal profile of thalweg elevation along Chaco Wash in the early 1930s and 2000. Dashed vertical lines indicate the location of the Chaco trench and important cultural landmarks.

lished on the margins of Chaco Wash in 1939 (at HD = 69 m on Plate 2 [see footnote 1]) and in 1944 (at HD = 6 m). Sedimentation was rapid from 1951 through 1955 (>13 cm/yr) and subsequently decreased (Fig. 5B). The data understate this conclusion, because some of the 1951–1955 deposits were below the trench, and because parts of these deposits were subsequently eroded (e.g., HD < 44 m; Plate 2 [see footnote 1]). Sediment deposited in 1951–1955 could have been as much as double the amount shown by the data, based on inferences made from dated contacts located deep in the stratigraphic section. Sedimentation was comparatively moderate after 1955, typically ~2 or 3 cm/yr, except for the period 1971–1975, when the rate was close to 9 cm/yr (Fig. 5B).

After 1931, Chaco Wash undermined the arroyo wall on the left bank (Plate 2 [see footnote 1]), causing the arroyo to widen by 22 m (Fig. 6). This likely occurred during large floods that were frequent in the 1930s (Dabney Ford, Chaco Culture National Historical Park, 1991, personal commun.) and occurred before 1944, as indicated by a tree that sprouted on the streambed at the foot of the left arroyo wall in 1944 (HD = 6 m on Plate 2 [see footnote 1]). This erosion widened the arroyo by 33%, and no additional wall retreat occurred at the trench site between 1944 and 2000. The increase in arroyo area caused by wall retreat was counterbalanced by floodplain aggradation, which decreased average arroyo depth by 2.2 m (33%), resulting in a net decrease in arroyo cross-sectional area of 50 m^2 (11%) between the early 1930s and 2000 (Fig. 6).

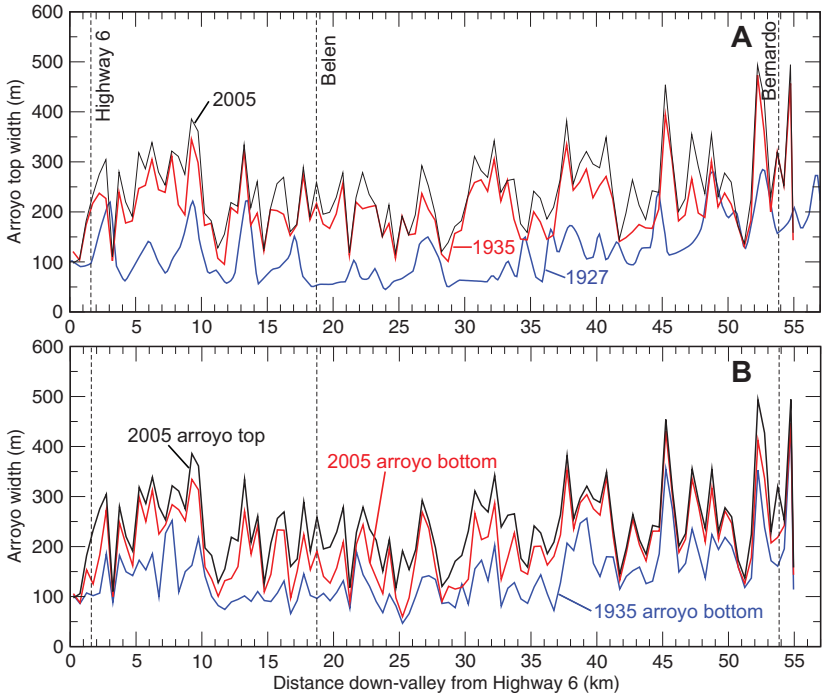


Figure 7. Change over time in the longitudinal variation of Rio Puerco arroyo width. (A) Arroyo top width in 1927, 1935, and 2005. (B) Arroyo bottom width in 1935 and 2005, with 2005 arroyo top width for comparison. Lines represent 0.5 km averages. Data are from Bryan and Post (1927) and from aerial photographs. Dashed vertical lines indicate the locations of the three trench sites.

Arroyo Scale

Longitudinal Variation in Rio Puerco Arroyo Properties

Application of trench data to address erosion and deposition at the arroyo scale requires additional arroyo-scale data. This is most apparent for plan-view attributes such as 0.5 km average arroyo top width, which fluctuates over a downstream distance of a few kilometers by as much as a factor of 3.6 (Fig. 7A). Arroyo bottom width varies over a wider range because of the presence of inset terraces at some locations, but not others. The 0.5 km average bottom width varies from a minimum of 60 m at vk 25.2 to a maximum of 447 m (7.5 times the minimum) at vk 54.7, near the Bernardo trench site (Fig. 7B). Accurate calculations of change in arroyo volume over time require repeat observations of these arroyo attributes at a scale broad enough to encompass downstream variability.

Longitudinal variations in elevation of the valley floor, floodplain, and channel thalweg are more subdued because they have been graded by the river. The longitudinal profile of the Rio Puerco floodplain is more regular than those of the valley floor or the channel thalweg (Fig. 8A). The longitudinal profile of the valley floor is measured at the tops of the two arroyo walls. Where the arroyo approaches either side of the valley or crosses an alluvial fan, arroyo depth may increase. For example, between vk 8.0 and 12.5, the arroyo has eroded east into steep adjacent slopes, increasing the valley floor elevation in this area by a meter or more compared to the west-side valley floor elevation, which is toward the pre-arroyo center of the valley.

There are two factors contributing to variability in the longitudinal profile of the thalweg. First, because the longitudinal profile distance is referenced to the arroyo centerline, the local channel gradient increases with increasing sinuosity and is influenced by the local channel orientation with respect to the arroyo (Fig. 8A). Second, thalweg gradient varies locally in response to variations in sediment supply, adjustment to meander cutoffs, and the local occurrence of resistant clay layers. For example, the modern thalweg gradient (2002–2005) is steep from vk 15.2 to 19.2 (Fig. 8A), apparently because of sediment supplied to the channel at two locations of arroyo wall erosion just upstream from this reach and from gullies draining steep adjacent hillslopes.

The longitudinal profile of the floodplain shows less variability because the floodplain is graded by deposition during overbank flows oriented in the down-valley direction and because each point in Figure 8A is the average elevation of the floodplain along a cross section. Coarser-scale variations in longitudinal profiles reflect interaction with the Rio Grande in two ways. First, because the Rio Grande is relatively unincised, the depth of the Rio Puerco arroyo necessarily declines close to their confluence. Second, there is a decrease in floodplain gradient downstream of vk 39 caused by back-water effects of a delta at the mouth of the Rio Puerco, which reached a maximum when erosion peaked in the 1930s (Fig. 8A; see Discussion section). Erosion of the delta by the Rio Grande caused re-incision of the Rio Puerco; as a result, the floodplain is higher above the channel downstream of vk 39 than anywhere else in the study area (Fig. 8A).

The effect of arroyo width and depth on longitudinal variation in arroyo volume is scale dependent. At the 1 km scale, longitudinal variation in arroyo volume (Fig. 9A) is dominated by the large variability in arroyo width (Fig. 7). At a

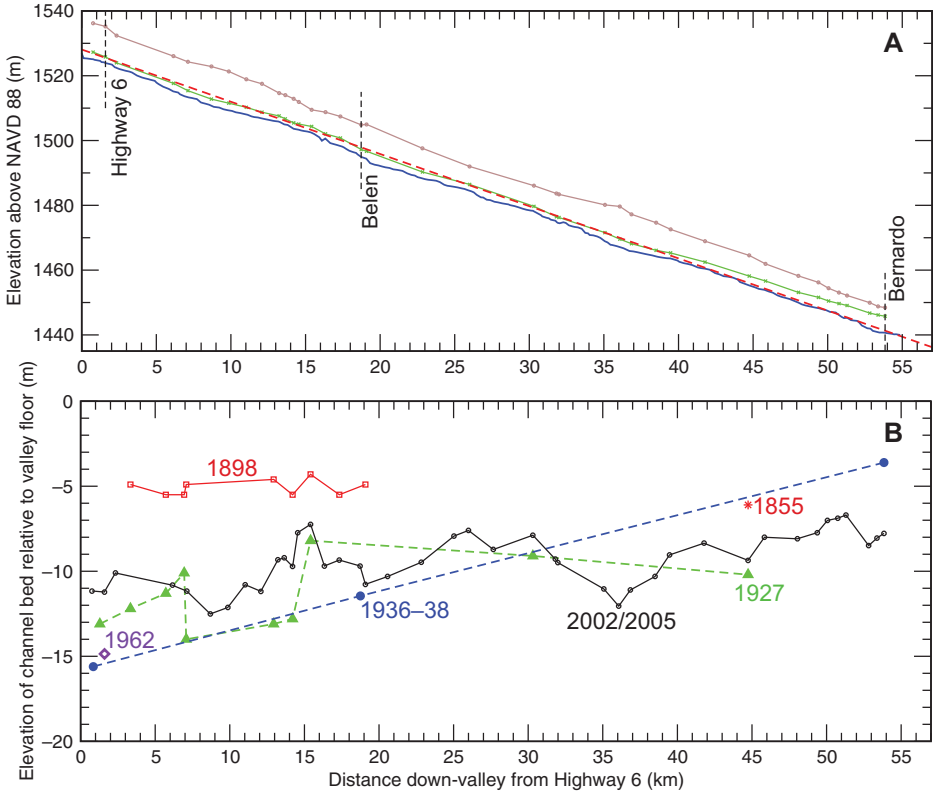


Figure 8. Longitudinal variation in elevation of channel bed, floodplain, and valley floor as a function of distance (km) down valley along the arroyo centerline (vk), Rio Puerco, New Mexico. (A) Longitudinal profiles of valley floor, floodplain, and thalweg prior to the August 2006 flood. Brown line is valley floor elevation from 2005 light detection and ranging (LiDAR) digital terrain models (DTMs); green line is average floodplain elevation from 2005 DTM arroyo cross sections; blue line is April 2002 global positioning system (GPS) surveyed thalweg. The red dashed line is a linear regression through the average floodplain elevations, vk 0–39 (n = 26, r = –0.9996). The equation for this line is $elev_{fp}$ = 1528.086 – 0.00161 × *valcldist*, where $elev_{fp}$ is the estimated floodplain elevation (m) and *vlcldist* is the distance (km) down valley from Highway 6 along the arroyo centerline. (B) Changes in height of the arroyo bottom (channel bed) below the valley floor since the mid-1800s. Data from 1855, 1898, and 1927 were collected by J.W. Garretson, G.H. Pradt, and G.M. Post (Bryan, 1928). The 1930s data (blue line) include K. Bryan's 1936 cross section (Elliott et al., 1999) and trench stratigraphy at the Belen and Bernardo trench sites in 1937 and 1938. The 1962 point (violet diamond) is from the Highway 6 trench stratigraphy, and the black line is from the 2002 GPS survey and 2005 LiDAR DTMs.

broader scale, however, variation in arroyo width is subdued, and much of the variation in arroyo volume is related to arroyo depth (Fig. 9A). This pattern consists of increases for vk 0–9, 15–21, and 25–37, and decreases for vk 9–15, 21–25, and 38–54.

The channels within the rapidly filling arroyos at Rio Puerco and Chaco Wash are exceptionally regular, narrow, and deep (Figs. 6A, 10, and 11; Plate 1 [see footnote 1]), giving the impression of a constructed canal or a downcutting channel. Trench stratigraphy and historical imagery demonstrate, however, that the narrow trapezoidal channel is a stable depositional feature of filling arroyos and is not human-made. The Rio Puerco study reach is only locally affected by engineering works, and in most cases, these works maintain only the position, not the shape of the channel. Historic aerial photographs show that the current narrow channel at the bottom of the arroyo developed with little human influence by gradual narrowing over several decades (Figs. 3 and 12). Trenches at Chaco Wash, Highway 6, and Belen all show a strongly depositional cross section featuring a decades-long gradual process of channel narrowing by bank encroachment and channel aggradation (Plates 1 and 2 [see footnote 1]). This process has occasionally been interrupted by temporary widen-

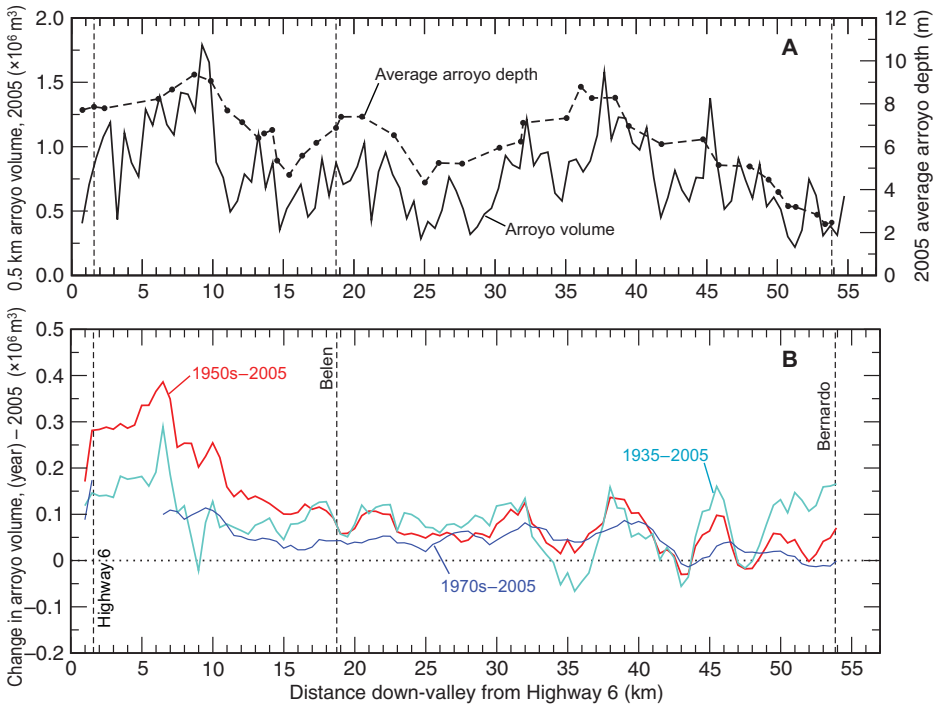


Figure 9. Variation over space and time in arroyo volume and depth along the Rio Puerco. (A) Arroyo volume in 0.5 km sections and average arroyo depth in 2005 as a function of distance down valley along the arroyo centerline. (B) Arroyo volume in 1935, 1950s, and 1970s relative to that of 2005, smoothed using a 2.5 km running average.

Figure 10. Photograph of a typical trapezoidal channel, Rio Puerco vk 13.22, 3 April 2010, by E. Griffin, where vk is down-valley distance in valley kilometers.

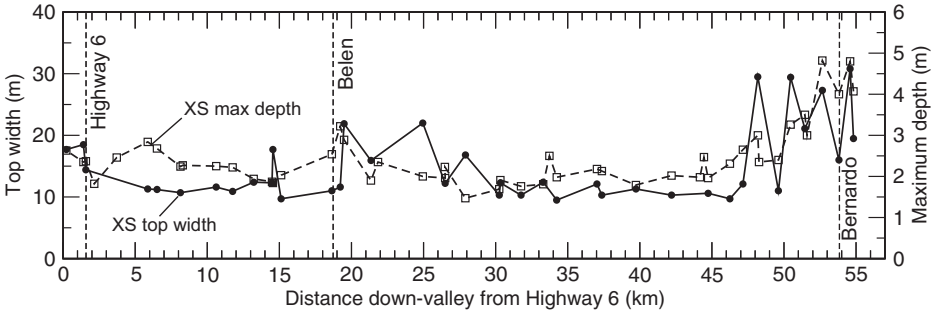


Figure 11. Longitudinal variation in channel top width and maximum depth measured in cross sections along the Rio Puerco, New Mexico, April 2002. XS—cross section.

ing and deepening during floods that produced erosional contacts preserved in the trenches, for example, the pair of cutbanks preserved in the Belen trench at HD = 157 m (Plate 2 [see footnote 1]). The dominant process, however, is channel narrowing by bank encroachment and thalweg aggradation at a wide range of flows.

Changes through Time

Rio Puerco. According to Bryan and Post (1927), the arroyo was shallow and discontinuous in the mid-1850s, and most arroyo cutting occurred in the 1880s and 1920s. At the upstream end of our reach, the arroyo was ~5 m deep in 1898 (Fig. 8B). By 1927, the arroyo was 8–14 m deep. Upstream of about vk 30, the arroyo reached its greatest depth around 1935 following the floods of record in 1929 (Fig. 8B). Downstream of vk 30, the greatest arroyo depth occurred around 1927 (Fig. 8B).

Arroyo widening occurs when fluvial erosion undercuts the arroyo wall, causing collapse, or when soil piping (Heede, 1971) or hillslope gully erosion removes sediment from the wall. As a consequence of channel incision and high flows, arroyo widening was rapid into the 1930s (Figs. 7A and 13B). From 1927 to 1935, arroyo top width nearly doubled. After 1935, as the channel narrowed and the arroyo began to fill, arroyo widening continued, but at a much slower rate (Figs. 7A and 13B), because erosive flow was less frequent, because a narrow channel in a wide arroyo rarely contacts the arroyo wall, and because the developing floodplain vegetation slowed channel migration. In fact, the increase in average arroyo top width in the eight years between 1927 and 1935 was greater than the increase in the 70 yr between 1935 and 2005 (Fig. 13B).

Incision and filling of the Rio Puerco arroyo have included the formation and destruction of

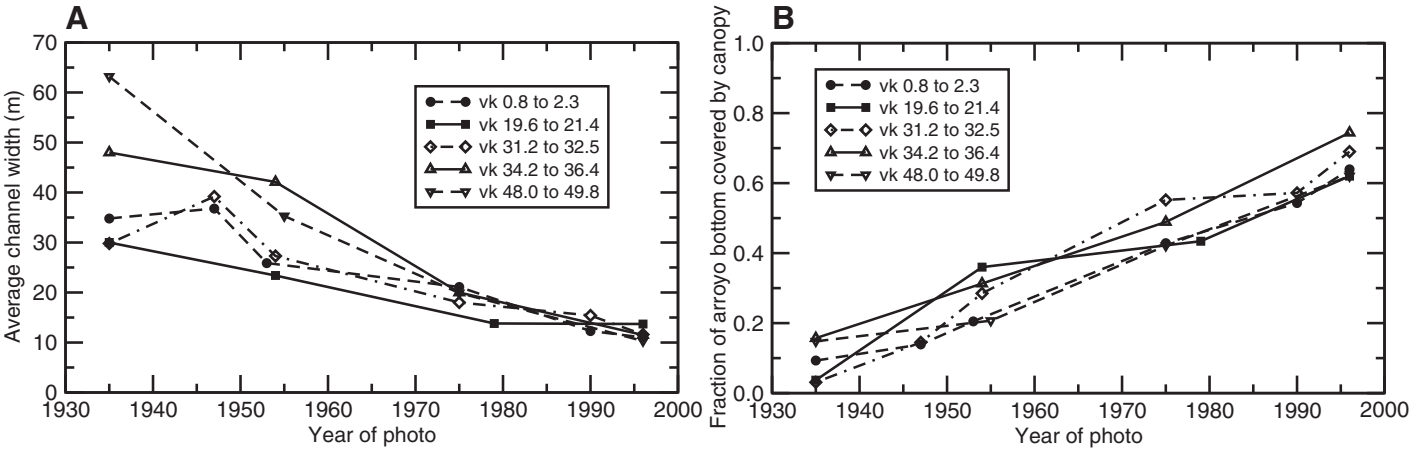


Figure 12. Change over time in (A) average channel width and (B) canopy cover in five subreaches of the Rio Puerco arroyo, New Mexico.

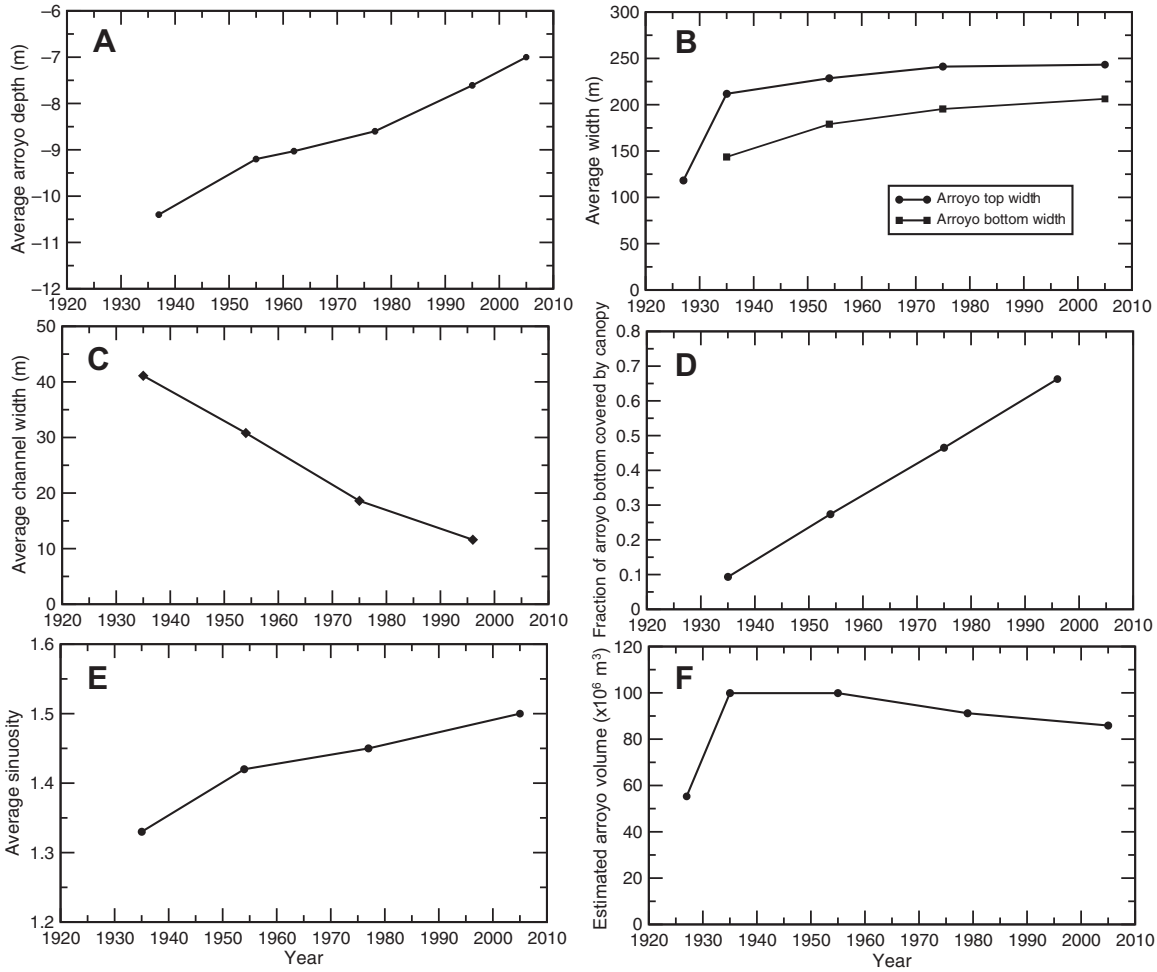


Figure 13. Changes over time in spatially averaged properties of the lower Rio Puerco arroyo during arroyo filling. (A) Arroyo depth (the incised reach, downstream of vk 39, is excluded; vk—down-valley distance in valley kilometers). (B) Arroyo top and bottom width. (C) Channel width. (D) Fraction of arroyo bottom covered by canopy. (E) Channel sinuosity. (F) Arroyo volume.

inset terraces. The episodic process of arroyo incision transformed channel and floodplain surfaces into inset terraces within some segments of the arroyo (Figs. 1 and 3; Fig. DR1 [see footnote 2]). Formation of inset terraces caused a large difference between arroyo bottom width, which includes only the floodplain and channel, and arroyo top width, which also includes inset terraces and arroyo walls (Fig. 7B). Inset terrace formation ended with the end of arroyo incision around 1935 (Figs. 1 and 8B), at which point mean arroyo top width was 68 m greater than mean arroyo bottom width (Fig. 13B). By the 1970s, channel meandering within the arroyo had eroded many of the inset terraces, and the difference between average arroyo top width and bottom width had decreased to 46 m (Fig. 13B). Between the 1970s and 2005, the rates of increase in arroyo top and bottom width were only ~1%, reflecting the low peak flows in this period, the narrow channel that contacted the wall infrequently, and the dense vegetation that retarded channel migration (Fig. 13B). As the floodplain continues to rise, it will eventually bury the inset terraces, as is beginning to happen at Highway 6 (HD = 150 m; Plate 2 [see footnote 1]; Fig. 1). This will continue to reduce the difference between arroyo top and bottom widths. A local exception to the rule of increasing arroyo bottom width over time has occurred at vk 29.7 (Fig. 7B), where two tributary gullies draining the steep east-side hillslope have created a large fan within the arroyo. Downstream of vk 37, the difference between arroyo top and bottom width is small (Fig. 7B), reflecting a scarcity of inset terraces. Here, proximity to the Rio Grande limited the depth of channel incision, reducing opportunities for inset terrace formation and increasing the amplitude of lateral erosion.

During the phase of arroyo cutting, vegetation was sparse, the channel was wide, and sinuosity was low (Figs. 13C and 13E). In the 1930s, arroyo incision ceased, arroyo widening greatly slowed, and channel narrowing and riparian vegetation establishment began. The process of arroyo filling at the Rio Puerco from the 1930s to the 2000s included channel narrowing, riparian vegetation proliferation, increased sinuosity, decreased channel gradient, floodplain development, and sediment deposition on the channel and floodplain (Figs. 12, 13, and 14). This process was made possible by previous arroyo widening, which decreased stream power in floods, and was promoted by decreased peak flows and deposition of sediment delivered from upstream erosion. From 1936 to 2010, the average arroyo depth decreased by 31% from 10.4 m to 7.2 m (Fig. 13A). Proliferation of vegetation was enhanced by introduction of

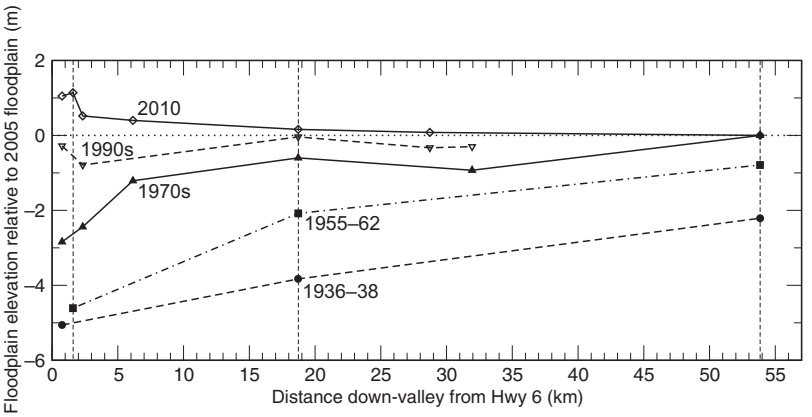


Figure 14. Average floodplain elevations estimated from surveyed cross sections and trench stratigraphy referenced to the average 2005 floodplain (dotted line). Some cross-section data from the 1970s and 1990s were provided by John Elliott, U.S. Geological Survey (2010, personal commun.).

non-native salt cedar in 1926. The proportion of arroyo bottom covered by woody vegetation (mostly salt cedar) increased from an average of 9.3% in 1935 to 66% in 1996 (Figs. 12 and 13D). Over the same period, average channel width decreased by almost a factor of 4, from 41 m to 12 m (Figs. 10 and 13C). Reach-average channel sinuosity increased 12.8% from 1.33 in 1935 to 1.50 in 2005 (Fig. 13E). Variability in sinuosity also increased, with the standard deviation computed from 111 values for 0.5 km arroyo segments increasing from 0.39 in 1935 to 0.53 in 2005. As woody vegetation proliferated, channel migration slowed; after the 1970s, channel migration was limited to locations where banks were unprotected by vegetation, especially where channel bends contacted the high arroyo wall (Fig. 15).

The transition from arroyo incision to aggradation is shown in the record of arroyo volume. From 1927 to 1935, rapid arroyo widening and deepening enhanced by the flood of record in 1929 almost doubled arroyo volume from 55.3 to 99.9 × 10^6 m^3 (Fig. 13F). From 1935 to 1955, arroyo widening was much slower and was counterbalanced by deposition within the arroyo, resulting in no net change in volume. From 1955 to 1979, deposition within the arroyo far outpaced erosion from arroyo widening, resulting in decreased arroyo volume by a total of 8.7 × 10^6 m^3 (8.7%). This trend continued from 1979 to 2005 (Fig. 13F), although the decrease (5.3 × 10^6 m^3, 5.8%) was smaller because of relatively low peak flows and reduced sediment inflow (Fig. 4).

Chaco Wash. As at Rio Puerco, arroyo widening at Chaco Wash greatly slowed after the 1930s. The increase in arroyo top width at the Chaco trench from the 1930s to 2000 of 33% (Fig. 6A) occurred almost entirely before 1944 (see Trench-Scale results for Chaco Wash). This was larger than the mean increase for the 1500 m study reach of 13.9% (Fig. 6B), from 71.0 to 80.9 m. Although there was no downstream trend in arroyo top width in either the 1930s or 2000, there was local variation of almost 100 m, and the magnitude of variation decreased downstream (Fig. 6B) in association with a decrease in arroyo sinuosity.

Topographic surveys in the 1930s and 2000 allow a detailed comparison of longitudinal profiles (Fig. 6C). The mean rise in the thalweg of 0.43 m is only slightly less than the value at the trench of 0.51 m (Fig. 6A). Most of the arroyo filling at Chaco Wash has occurred as channel narrowing and floodplain accretion, not aggradation of the thalweg (Fig. 6A; Plate 2 [see footnote 1]). This history is similar to that of the Highway 6 trench along the Rio Puerco prior to the 1980s.

As at the Rio Puerco, channel narrowing at Chaco Wash between 1930 and 2000 occurred by a process of bank encroachment and levee formation. In the 1930s, mean channel width was 43.6 m (Fig. 6B), and channel width at the trench was 43.5 m. By 2000, channel width at the trench had decreased by a factor of 8.8–5.0 m as riparian vegetation proliferated on the floodplain.

DISCUSSION

Sediment Storage within the Filling Arroyo

The net decrease in arroyo volume at the Rio Puerco from 1955 to 2005 was 1.4 × 10^7 m^3 or 14% (Fig. 13F), an average annual rate of 280,000 m^3/yr. At this rate, the remaining 8.6 × 10^7 m^3 would fill in 310 yr, lower than the estimate of 440 yr (from 1995) by Gellis and Elliott (2001) on the basis of a single cross section near Highway 6. An alternative estimate of filling time can be made by extrapolating the time trend for average arroyo depth (Fig. 13A), which decreased relatively steadily from 10.4 m in 1936 to 7.0 m in 2005. At this rate (4.9 cm/yr), the arroyo would fill in another 140 yr; because the width of the arroyo increases closer to the valley floor, maintaining this rate of decreasing depth would require accelerating deposition in terms of annual volume. Two past arroyos in the study reach were estimated to have filled from A.D. 900 to 1250 and from A.D. 1325 to 1450 (Love and Young, 1983). These filling times are mostly within the range of 200–700 yr calculated by Emmett (1974) based on extrapolation from early filling rates at eight southwestern U.S. sites.

Changes in sediment storage related to arroyo cutting and filling have been contemporaneous with decreases in sediment transport in both the Rio Puerco and the Rio Grande. Between 1948 and 1984, the suspended sediment concentrations at the Bernardo gauge decreased by more than 50% (Gellis and Elliott, 2001), while peak discharges were declining (Fig. 4). This decrease in sediment transport can be attributed to the change from arroyo cutting to filling at the study site as well as a decrease in erosion upstream and lower flows (Gellis et al., 2012). The Rio Puerco is a major source of sediment to Elephant Butte Reservoir on the Rio Grande (Fig. 2; Love 1986). Sediment accumulation in this reservoir declined from 30.3 × 10^6 m^3/yr (or 0.93% of full capacity per year) for 1915–1925 to 4.7 × 10^6 m^3/yr for 1988–1999 (Collins and Ferrari, 2000).

Arroyo filling influences the sediment output from the Rio Puerco. Sediment storage within the Rio Puerco arroyo between Highway 6 and Bernardo was 14 × 10^6 m^3 between 1955 and 2005 (Fig. 13F), an average annual rate of 4.8 × 10^5 t/yr. Mean suspended sediment load at the Bernardo gauge between 1955 and 2005 was 3.06 × 10^6 t/yr. Therefore, the average annual sediment storage within this section of the arroyo between 1955 and 2005 was ~16% of the average annual suspended sediment load of the Rio Puerco near the mouth over the same period. This rate of sediment storage within our 55 km study reach was 24% of the long-term bedrock denudation rate of the basin determined from cosmogenic isotopes (2.0 × 10^6 t/yr; Clapp et al., 2001; Bierman et al., 2005). Although the study reach of the Rio Puerco has been filling for more than half a century, upstream tributaries are still eroding (Gellis et al., 2012). As a result, the sum of the average annual storage

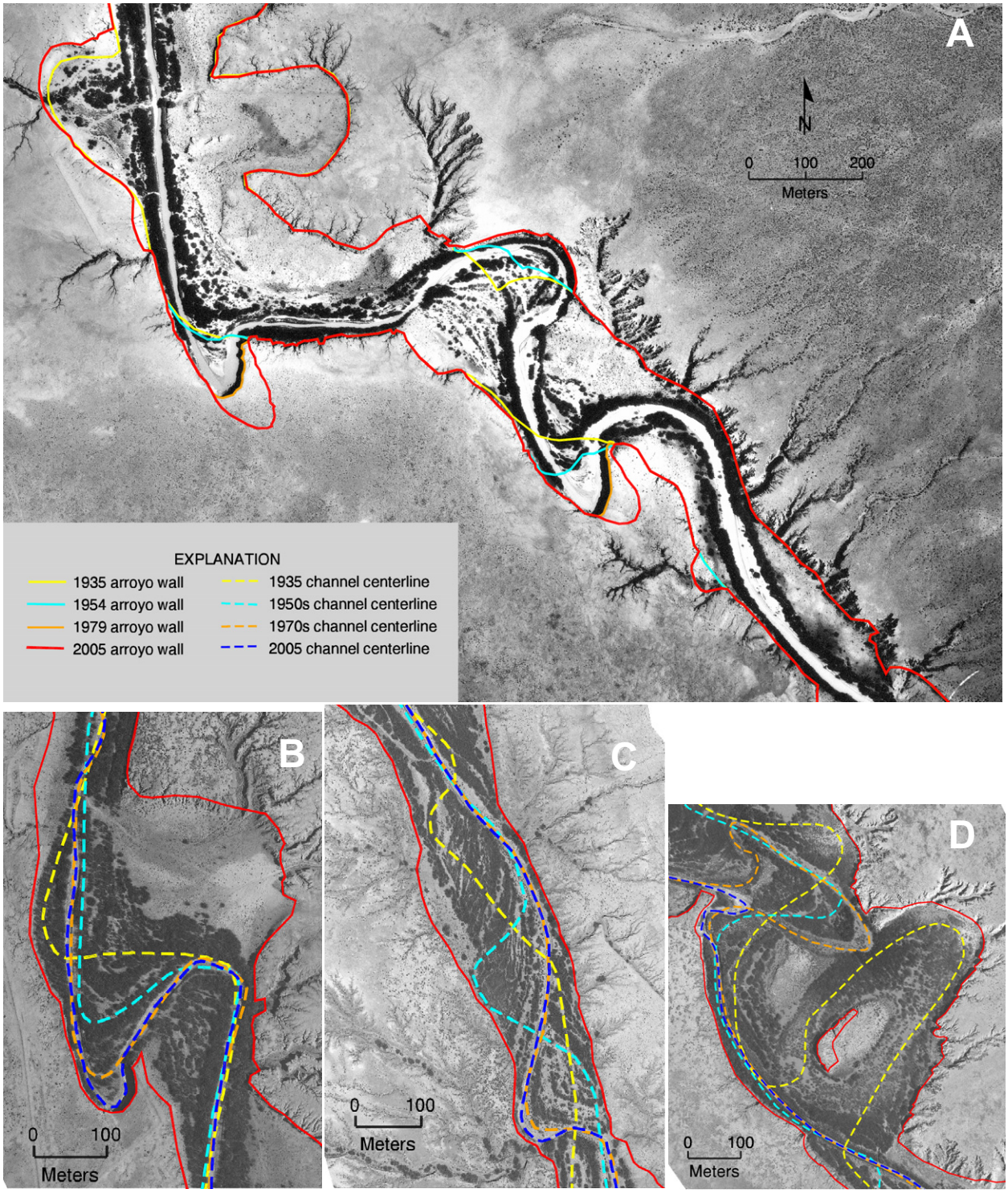


Figure 15. Channel migration and erosion of the arroyo wall along the Rio Puerco, New Mexico. In all cases, channel flow is from top to bottom of the page, and north is toward the top of the page. (A) Development of trapped bends over time. The image was acquired on 30 May 1979. Overlain are the locations of the arroyo wall in 1935, 1954, 1979, and 2005. The subreach shown extends from vk 12.9–14.9, where vk is down-valley distance in valley kilometers. (B) At vk 22.4, the bend migrated ~100 m down the arroyo from 1935 to 1954, but since the 1970s, it has been trapped against the arroyo wall and has eroded into valley fill. The image was acquired in 2005. (C) A narrow arroyo segment at vk 50.7 where the bend apex migrated a total of ~480 m down the arroyo between 1935 and 1975. Since 1975, the channel has remained fixed in place except at the bend apex cutting into the west arroyo wall. The rate of down-valley migration was ~12 m/yr from 1935 to 1975. The image was acquired in 2005. (D) At vk 9.6, extension of bends from the 1930s to the 1970s formed two islands of valley fill within the arroyo. The image was acquired in 2005.

within the study reach and the average annual suspended sediment discharge at Bernardo is 3.54×10^6 t/yr, which is 75% greater than the long-term bedrock denudation rate of the basin.

Approximate arroyo filling rates can be calculated at Chaco Wash on the basis of changes at the trench (Fig. 6A). Extrapolating from the 11.4% decrease in arroyo cross-sectional area between the early 1930s and 2000, the arroyo would fill in ~530 more years. Extrapolating from the 33.4% decrease in average arroyo depth over the same period, the arroyo would fill in another 140 yr.

Causes of the Shift from Arroyo Cutting to Filling

The shift at the lower Rio Puerco and Chaco Wash from arroyo cutting to filling roughly coincided with other similar shifts beginning in the mid-1900s in arroyo systems throughout the southwestern United States (Emmett, 1974; Hereford, 1984; Graf, 1987; Balling and Wells, 1990; Webb et al., 1991; Hereford et al., 1996). Several factors contributed to this regional shift. First, flood frequency and intensity decreased. In some cases, decreased flooding was driven by a reduction in precipitation intensity (Webb et al., 1991). At the Rio Puerco, however, intensity of the most extreme rainfall events did not decline (Molnar and Ramirez, 2001), suggesting that the decrease in flood magnitude (Fig. 4) resulted from flood attenuation by the developing floodplain and forest (Vivoni et al., 2006). This hypothesis is supported by the fact that peak flows have decreased more at the downstream end of the study reach than at the upstream end (Fig. 4). Second, strengthened regulation of livestock grazing, including passage of the federal Taylor Grazing Act in 1934, allowed vegetation cover to increase, stabilizing sediment within and adjacent to the arroyo and reducing upland runoff (Hereford et al., 1996). At the Rio Puerco, increasing vegetation cover was also promoted by an increase in mean precipitation (Molnar and Ramirez, 2001). Third, the shift was promoted by autogenic processes. For example, arroyo widening promotes vegetation development by decreasing boundary shear stress along the channel bed, and an upstream propagating wave of incision promotes downstream narrowing by increasing downstream sand transport (Schumm and Parker, 1973). Fourth, introduction and spread of salt cedar at the Rio Puerco, Chaco Wash, and elsewhere contributed to proliferation of vegetation on the floodplain (Shafroth et al., 2005). Where the salt cedar grew more densely than the previous plant community, this vegetation change may have increased flood attenuation by increasing fluid drag, reduced floodplain erosion by slowing flow near channel banks, and reduced bank collapse by root reinforcement (Bryan and Post, 1927; Graf, 1978; Kean and Smith, 2004; Vincent et al., 2009). A beetle (*Diorhabda* spp.) introduced to North America to control salt cedar is dispersing into the Rio Puerco and Chaco River watersheds (Tamarisk Coalition, "Yearly distribution (2007-2013) of Tamarisk Leaf Beetle [*Diorhabda* spp.]" http://www.tamariskcoalition.org/sites/default/files/images/Tamarisk_Coalition_2013_TLB_Distribution_Map_Final.jpg). If this insect kills the salt cedar in the arroyo and reduces vegetation density, renewed incision and increased downstream sediment delivery could result.

Upstream Progression

Models of arroyo evolution include upstream-traveling waves of incision, aggradation (Bull, 1997; Elliott et al., 1999), and in some cases re-incision (Schumm and Parker, 1973). To what extent have changes along the Rio Puerco arroyo propagated upstream? Upstream propagation of headcuts has been documented in our study reach at a local scale. For example, a headcut related to erosion of an 18-cm-thick clay layer in the channel bed migrated upstream past the Bernardo gauge in 1961 (Nordin, 1963). In the process of surveying the longitudinal profile, we observed similar small headcuts associated with the breakup of resistant clay layers (Fig. 8A). At the scale of the whole study reach, however, the data from the time of incision are sparse (Fig. 8B), and incision is rapid and episodic. As a result, the importance of upstream propagation of incision is difficult to assess. Historic observations indicate that in the mid-1800s, the study reach was incised in some areas but not in others; after erosion by floods, especially in the 1880s, the entire reach was probably incised by 1896 (Bryan, 1928; Love 1997). Upstream from the study reach, incision was sometimes initiated or enhanced by local disturbances, including channel avulsion related to dam failure or flow diversion (Bryan, 1928; Love, 1997). Therefore, incision appears to have been initiated at multiple points, and to have increased in some cases by processes other than knickpoint migration (Love, 1997). Although our data showed no clear evidence of upstream propagation of incision, we did observe upstream propagation of the subsequent process of arroyo widening. In 1927, the arroyo was considerably wider downstream from vk 44 than upstream, but between 1927 and 1935, this contrast was mostly eliminated by greater widening upstream (Fig. 7A).

Time-transgressive behavior is evident within the study reach in the timing of the transition from cutting to filling and in the rate of filling. These patterns are clear in part because upstream propagation of deposition was relatively slow, because the period of deposition occurred in recent decades, which are better documented, and because stratigraphy preserves evidence of deposition better than evidence of erosion. At the end of the period of rapid erosion in the mid-1930s, the elevation drop along the study reach was low. Thalweg elevation had reached a minimum at the upstream end of our reach, but at the downstream end, filling had already occurred, and thalweg elevation had reached a temporary high (Fig. 8B). Sediment evacuated from the Rio Puerco had been deposited as a delta at the confluence with the Rio Grande, resulting in aggradation by 1936 at the downstream end of our reach (Fig. 8B). Tuan (1966) reported aggradation of 4.3 m along the Rio Puerco near the mouth by ca. 1940, which is corroborated by channel deposits preserved in the trench at Bernardo (Plate 2 [see footnote 1]). Since that time, a steeper arroyo gradient has been reestablished through erosion at the downstream end and deposition at the upstream end of the study reach. The delta at the mouth was partially removed by alluvial sediment transport and human channel modification, resulting in re-incision of the lower part of our reach in the 1940s–1960s as far upstream as vk 38 (Fig. 8B; Tuan, 1966; Welsh, 1985). Between 1936 and 2002, the thalweg aggraded by 3.9 m at Highway 6, aggraded by 2.6 m at Belen, and degraded by 4.1 m at Bernardo (Fig. 8B). It is interesting to note that average stream gradient in the study reach was about the same in 2002 as it was in the 1930s, ~0.0011, because the increase in elevation drop was counterbalanced by an increase in channel sinuosity (Fig. 13E).

Floodplain sediment deposition has progressed upstream since 1936. At the Bernardo trench, sediment deposition was most rapid in the 1940s and subsequently slowed; there was no sediment deposition on the floodplain between 1972 and trench excavation in 1999 (Plate 2 [see footnote 1]; Figs. 5B and 14). At Belen, aggradation was most rapid in the 1950s and 1960s. At Highway 6, rapid aggradation began in the 1960s and continues today (Plate 2 [see footnote 1]; Figs. 5B and 14).

Time transgression in the transition from arroyo incision to aggradation is summarized by shifts in arroyo volume. Between 1927 and 1935, arroyo volume increased throughout the study reach as a result of arroyo widening and deepening. From 1935 to 1955, arroyo volume continued to increase in the upstream third of the study reach, where erosion due to arroyo widening exceeded deposition due to floodplain aggradation (Fig. 9). In contrast, during the

same time period, arroyo volume decreased in the downstream third of the study reach, where floodplain aggradation outpaced arroyo widening (Fig. 9). Arroyo volume increased by 2.86×10^6 m^3 (7.9%) from 1935 to 1955 from vk 0 to 16.5 (Fig. 9). Arroyo volume decreased slightly by 0.59×10^6 m^3 (1.8%) from vk 16.5 to 37.0 and decreased substantially by 2.28×10^6 m^3 (7.4%) from vk 37.0 to 55.0 (Fig. 9). The net effect of these changes was a downstream shift of sediment within the study reach; there was little overall change in arroyo volume during this period (Fig. 13F). By the next interval (1955–1979), deposition from floodplain aggradation was exceeding erosion from arroyo widening throughout the study reach, and this trend of decreasing arroyo volume throughout the study reach continued from 1979 to 2005 (Figs. 9 and 13F). At the scale of the whole arroyo, the shift between incision and aggradation is still propagating upstream. Incision was complete in the study reach by 1935, but it was still active upstream on the main-stem Rio Puerco in the 1970s (Elliott et al., 1999). Two decades later, most of Elliott's cross sections in the upper Rio Puerco were no longer incising (Elliott et al., 1999), but incision in tributaries continues today (Gellis et al., 2012).

The decrease in channel width and increase in shrub canopy cover that accompany arroyo evolution might also be expected to progress as a wave upstream over time, but this is not evident within the study reach. Longitudinal trends in the rate of channel narrowing have been driven by large initial differences in channel width (Fig. 12A). The widest subreaches in 1935 were the two furthest downstream (Fig. 12A), a result of the extreme upstream erosion in the preceding decade that temporarily aggraded the thalweg at Bernardo (Fig. 8B). In subsequent decades, all subreaches narrowed and approached a similar width by 1996 (Fig. 12A). Development of a shrub canopy occurred approximately synchronously across subreaches (Fig. 12B). Trends in channel width and vegetation cover show the expected time-transgressive pattern only when viewed at the scale of the whole arroyo system. Channel narrowing occurred later upstream of the study reach (Elliott et al., 1999), and wide reaches with sparse vegetation are still common in the upper Rio Puerco.

Autogenic models of arroyo development predict upstream-traveling waves of incision, deposition, and then re-incision (Schumm and Parker, 1973; Bull, 1997; Elliott et al., 1999; Gellis et al., 2012). These predictions have been at least partially confirmed in some cases (Patton and Schumm, 1981; Bull, 1997), but not others (Karlstrom and Karlstrom, 1987; Hereford, 2002). Time transgression may be undetected if it occurs too rapidly over the reach examined for the dating technique employed. Time transgression may be blocked by other factors, such as local bedrock control, which prevents passage of knickpoints (Webb et al., 1991), complicated by multiple points of incision, or obscured by downstream variation in tributary flow (Graf, 1980) or by local human influences like channelization or dam failure (Love, 1997). The study reach at Chaco Wash, like those of most other arroyo investigations, was too short to demonstrate patterns of time transgression in any characteristics of arroyo development. At the Rio Puerco, our use of dating with annual precision at multiple trenches in a long reach (55 km) combined with coarser-scale observations of arroyo change allowed detection of upstream progression for arroyo widening, the transition from incision to filling, and arroyo filling, and we observed re-incision at the mouth as predicted by Schumm and Parker (1973). On the other hand, we did not observe time transgression for arroyo incision, channel narrowing, or floodplain vegetation development within our study reach.

Narrow Trapezoidal Channel Is Maintained by Vegetation and Sediment Deposition

The low width-to-depth ratio and low longitudinal variability of the channels within the arroyos of Rio Puerco and Chaco Wash are maintained by bank vegetation and the strongly depositional sediment transport regime. Fluid drag on willow and salt cedar stems along the Rio Puerco decreases shear stress at the toe of the bank by an order of magnitude (Kean and Smith, 2004), reducing erosion of the channel banks. Reduced shear stress and flow velocity in the near-bank region of the flow cause deposition of sand in suspension onto the banks. Root reinforcement of banks increases their resistance to mass failure (Simon and Collison, 2002; Pollen-Bankhead et al., 2009). The importance of bank vegetation in controlling channel width is demonstrated by the contemporaneous decrease in channel width and increase in floodplain shrub cover since the 1930s (Figs. 13C and 13D). As bank vegetation has developed, the potential for channel erosion during floods has decreased (Griffin et al., 2005, 2014). Even during the flood of 2006, the largest since 1972 (Fig. 4), erosion was limited to locations where the bank vegetation had been killed by herbicide, and locations where bank vegetation was absent because the channel was cutting into the arroyo wall (Vincent et al., 2009).

The strongly depositional sediment transport regime promotes proliferation of dense vegetation along the narrow channel. While riparian plants can be removed by sediment erosion, these plants survive sediment deposition of more than a meter in a single event and several meters over decades (Plate 2 [see footnote 1]; Hupp, 1992; Dean et al., 2011). In rapidly aggrading reaches of the Rio Puerco, the bank and bed include buried stems and roots that increase fluid drag if exposed by minor erosion and produce new sprouts throughout the growing season. Therefore, a strongly depositional sediment transport regime promotes extreme narrowing by reducing erosion and minimizing damaging effects of high flow on vegetation. This results in the strongest possible effect of vegetation on shear stress and bank stability. In summary, channel narrowing in a filling arroyo is enhanced by positive feedback between vegetation density and sediment deposition. We predict similar narrow, regular channels within other rapidly filling arroyos in the presence of dense riparian vegetation.

Channel maintenance by sediment deposition results in low longitudinal variation in channel dimensions (Fig. 11). Along a channel enlarged by erosion, overbank flows would be rare, and channel dimensions would vary longitudinally, reflecting the cumulative effects of local erosion history. In contrast, along the Rio Puerco and Chaco Wash, past channels are buried, and current channel dimensions are dominated by deposition in recent flows, resulting in subdued downstream variation in channel dimensions (Fig. 11). Much of the relatively small longitudinal variation in channel dimensions is related to variation in plant stem density. For example, the wider reach from vk 20 to 30 (Fig. 11) is associated with unusually sparse vegetation (Griffin et al., 2005). The one exception to the rule of stable depositional channels is at the downstream end of the Rio Puerco study reach including the Bernardo trench. As a result of the deposition and re-incision of a delta at the mouth of the Rio Puerco (see earlier in Discussion section), channel depth and volume increase gradually downstream of about vk 50 (Fig. 11). In this erosional reach, sediment deposition on the floodplain has almost ceased (Fig. 5B), and longitudinal variation in channel width is large, reflecting local variation in the history of recent erosion (Fig. 11; Griffin et al., 2005, 2014).

Erosion of High Arroyo Walls Leads to Trapped Bends

Channel narrowing along the Rio Puerco produced a narrow, relatively sinuous channel that migrated across the floodplain, occasionally contacting the arroyo wall. Channel migration was rapid through the 1960s but then slowed because of decreased peak flows

(Fig. 4) and increased bank stability provided by dense floodplain shrubs (Fig. 15). Since the 1970s, channel migration has been limited to locations where the outer bank of the bend is unprotected by vegetation, especially where a channel bend erodes locally into valley-fill sediment by undercutting the arroyo wall. The channel may become trapped at such locations (Fig. 15). More precisely, the apex of the bend may continue to erode into the valley fill, while the channel approaching and exiting the bend remains fixed in place. Because erosion is highest on the outside of a bend just downstream of the bend apex, trapped bends tend to curve down valley back toward the arroyo as they grow.

Trapped bends develop because the valley wall along an outside bank is more susceptible to fluvial erosion than the floodplain. When a cutbank erodes into a floodplain, roots and buried stems of shrubs increase bank stability (Simon and Collison, 2002) and reduce shear stress near the bank and at the bank toe (Kean and Smith, 2004; Griffin et al., 2005). Roots of plants growing on top of the arroyo wall are not deep enough, however, to stabilize the channel bank or exert drag on the flow. In addition, the height of the valley wall makes it more susceptible to cantilever failure following erosion at the toe (Van de Wiel and Darby, 2007). Along channel banks undercutting the arroyo wall, repeated collapse of the wall prevents establishment of vegetation, and the toe of the outer bank remains an area of high shear stress. Once the bend is trapped, the area of erosion develops a small radius of curvature (typically less than 1.5 times the channel width), increasing secondary flow and turbulence at the outside of the bend and allowing erosion to occur even at moderate flow (Smith and McLean, 1984; Kang and Sotiropoulos, 2011; Engel and Rhoads, 2012). Another factor maintaining a trapped bend is that in the next bend immediately downstream (Fig. 15), flow approaching the bend is oriented up valley, and as a result, during overbank flow, down-valley flow and down-channel flow are moving in opposite directions, reducing velocities and boundary shear stresses. A comparison of mapped channel locations in 1996 and 2005 indicates channel movement during that period of low peak flows was almost entirely at locations of trapped bends (Fig. 15).

CONCLUSIONS

A multiscale approach to investigation of the process of arroyo filling can provide both the temporal precision necessary to relate channel changes to hydrologic events and the spatial coverage necessary to quantify sediment storage. Burial signatures in tree rings of salt cedar and willow precisely date sedimentary beds. Beds thicker than 30 cm were generally dated with annual precision, making it possible to relate sedimentary units to specific flows. Most deposition occurred in overbank floods occurring one to a few times per decade following summer monsoonal thunderstorms.

The occurrence of time transgression over many decades within large basins like the Rio Puerco makes precise synchrony across basins impossible. Consistent with arroyo evolution models, the Rio Puerco demonstrated upstream progression of arroyo widening, the transition from incision to filling, and arroyo filling, followed by re-incision at the mouth. On the other hand, we did not observe upstream progression of arroyo incision, channel narrowing, or floodplain vegetation development within our study reach.

Sediment storage within a rapidly filling arroyo significantly reduces sediment delivery downstream. Sediment storage within the Rio Puerco study reach was 1.4×10^7 m^3 between 1955 and 2005, an average annual rate of 4.8×10^5 t/yr, which is ~16% of the average annual suspended sediment load of the Rio Puerco near the mouth, and ~24% of the long-term bedrock denudation rate of the basin determined from cosmogenic isotopes. At this rate, the remaining 8.6×10^7 m^3 would fill in another 310 yr. Because of large temporal and longitudinal variation in arroyo width, accurate calculations of changes in arroyo volume over time require repeat observations at a scale broad enough to encompass longitudinal variability.

Rapidly filling, densely vegetated arroyos are characterized by an extremely narrow, uniform channel. Although the channels of the Rio Puerco and Chaco Wash are narrow, like an erosional gully, and uniform, like a human-made ditch, they are in fact natural depositional features in which the dimensions are conserved even as floodplain and thalweg aggrade. The low width-to-depth ratio of these channels is caused by dense plant stems that reduce shear stress on the bank surface, buried stems and roots that increase bank strength, and a strongly depositional sediment transport regime that reduces erosion and damage to plants.

Bimodal bank heights skew meander geometry. Channel banks are normally protected from undercutting by dense stems and roots, but where the channel contacts the high arroyo wall, the bank toe is unprotected by vegetation. Where the channel impinges on the arroyo wall, the wall may erode, while the banks upstream and downstream do not, leading to formation of arcuate hairpin bends with a typical radius of curvature <1.5 times the channel width.

ACKNOWLEDGMENTS

This research was supported by the Global Change Research Program and the Central Region Integrated Science Program of the U.S. Geological Survey. The Pueblo of Isleta generously enabled the research to take place on their land and provided valuable historical and cultural information. Eligio Aragon of Alley Cat Excavating, Peralta, New Mexico, performed the precision backhoe work. Light detection and ranging (LiDAR) acquisition in 2005 was carried out by Spectrum Mapping, LLC, overseen by Vivian Queija. Chris Holmquist-Johnson, Zack Bowen, and Terry Waddle led the global positioning system surveys. John Elliott and Allen Gellis provided unpublished cross-section data from the Rio Puerco. Peggy Anderson assisted with the field work. Julie Fleming carried out much of the salt cedar sample preparation. Tammy Fancher assisted with figure preparation. Allen Gellis and two anonymous reviewers made valuable suggestions for improvement of the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

REFERENCES CITED

Balling, R.C., and Wells, S.G., 1990, Historical rainfall patterns and arroyo activity within the Zuni River drainage basin, New Mexico. Annals of the Association of American Geographers, v. 80, p. 603–617.

Bierman, P.R., Reuter, J.M., Pavich, M., Gellis, A.C., Caffee, M.W., and Larsen, J., 2005, Using cosmogenic nuclides to contrast rates of erosion and sediment yield in a semi-arid, arroyo-dominated landscape, Rio Puerco Basin, New Mexico. Earth Surface Processes and Landforms, v. 30, p. 935–953, doi:10.1002/esp.1255.

Boardman, J., 2014, How old are the gullies (dongas) of the Sneeuberg uplands, Eastern Karoo, South Africa. Catena, v. 113, p. 79–85, doi:10.1016/j.catena.2013.09.012.

Bryan, K., 1925, Date of channel trenching (arroyo cutting) in the arid southwest. Science, v. 62, p. 338–344, doi:10.1126/science.62.1607.338.

Bryan, K., 1928, Historic evidence on changes in the channel of Rio Puerco, a tributary of the Rio Grande in New Mexico. The Journal of Geology, v. 36, p. 265–282, doi:10.1086/623512.

Bryan, K., and Post, G.M., 1927, Erosion and Control of Silt on the Rio Puerco, New Mexico. Albuquerque, New Mexico, Report to the Chief Engineer, Middle Rio Grande Conservancy District, 348 p.

Bull, W.B., 1997, Discontinuous ephemeral streams. Geomorphology, v. 19, p. 227–276, doi:10.1016/S0169-555X(97)00016-0.

Clapp, E.M., Bierman, P.R., Nichols, K.K., Pavich, M., and Caffee, M., 2001, Rates of sediment supply to arroyos from upland erosion determined using in situ produced cosmogenic ^{10}Be and ^{26}Al. Quaternary Research, v. 55, p. 235–245, doi:10.1006/qres.2000.2211.

Collins, K., and Ferrari, R., 2000, Elephant Butte Reservoir, 1999 Reservoir Survey. Denver, Colorado, Sedimentation and River Hydraulics Group, Technical Services Center, Bureau of Reclamation, 126 p.

Cooke, R.U., and Reeves, R.W., 1976, Arroyos and Environmental Change. Oxford, UK, Clarendon Press, 213 p.

Dean, D.J., Scott, M.L., Shafroth, P.B., and Schmidt, J.C., 2011, Stratigraphic, sedimentologic, and dendrogeomorphic analyses of rapid floodplain formation along the Rio Grande in Big Bend National Park, Texas. Geological Society of America Bulletin, v. 123, p. 1908–1925, doi:10.1130/B30379.1.

Dodge, R.E, 1902, Arroyo Formation. Science, v. 15, p. 746.

Elliott, J.G., Gellis, A.C., and Aby, S.B., 1999, Evolution of arroyos: Incised channels of the southwestern United States, *in* Darby, S.E., and Simon, A., eds., Incised River Channels. Chichester, UK, Wiley, p. 153–185.

Emmett, W.W., 1974, Channel aggradation in western United States as indicated by observations at Vigil

Network sites. Zeitschrift für Geomorphologie, v. 21, p. 52–62.

Engel, F.L., and Rhoads, B.L., 2012, Interaction among mean flow, turbulence, bed morphology, bank failures and channel planform in an evolving compound meander loop. Geomorphology, v. 163–164, p. 70–83, doi:10.1016/j.geomorph.2011.05.026.

Friedman, J.M., Vincent, K.R., and Shafroth, P.B., 2005, Dating floodplain sediments using tree-ring response to burial. Earth Surface Processes and Landforms, v. 30, p. 1077–1091, doi:10.1002/esp.1263.

Gellis, A.C., 2002, Twentieth Century Channel Changes in Chaco Culture National Historic Park. U.S. Geological Survey Water Investigations Report 01-4251, 42 p.

Gellis, A.C., and Elliott, J.G., 2001, Arroyo changes in selected watersheds of New Mexico, United States, *in* Harvey, M., and Anthony, D., eds., Applying Geomorphology to Environmental Management; A Special Publication Honoring Stanley A. Schumm. Highlands Ranch, Colorado, Water Resources Publications, LLC Press, p. 225–240.

Gellis, A.C., Pavich, M.J., Ellwein, A.L., Aby, S., Clark, I., Wieczorek, M.E., and Viger, R., 2012, Erosion, storage, and transport of sediment in two subbasins of the Rio Puerco, New Mexico. Geological Society of America Bulletin, v. 124, p. 817–841, doi:10.1130/B30392.1.

Graf, W.L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region. Geological Society of America Bulletin, v. 89, p. 1491–1501, doi:10.1130/0016-7606(1978)89<1491:FATTSO>2.0.CO;2.

Graf, W.L., 1980, Fluvial processes in the lower Fremont River basin, *in* Picard, M.D., ed., Henry Mountains Symposium. Utah Geological Association Publication Number 8, p. 177–184.

Graf, W.L., 1987, Late Holocene sediment storage in canyons of the Colorado Plateau. Geological Society of America Bulletin, v. 99, p. 261–271, doi:10.1130/0016-7606(1987)99<261:LHSSIC>2.0.CO;2.

Griffin, E.R., Kean, J.W., Vincent, K.R., Smith, J.D., and Friedman, J.M., 2005, Modeling effects of bank friction and woody bank vegetation on channel flow and boundary shear stress in the Rio Puerco, New Mexico. Journal of Geophysical Research, v. 110, p. F04023, doi:10.1029/2005JF000322.

Griffin, E.R., Perignon, M.C., Friedman, J.M., and Tucker, G.E., 2014, Effects of woody vegetation on overbank sand transport during a large flood, Rio Puerco, New Mexico. Geomorphology, v. 207, p. 30–50, doi:10.1016/j.geomorph.2013.10.025.

Harvey, J.E., and Pederson, J.L., 2011, Reconciling arroyo cycle and paleoflood approaches to late Holocene alluvial records in dryland streams. Quaternary Science Reviews, v. 30, p. 855–866, doi:10.1016/j.quascirev.2010.12.025.

Heath, D.L., 1983, Flood and Recharge Relationships of the Lower Rio Puerco, New Mexico [Master's thesis]. Socorro, New Mexico Institute of Mining and Technology, 214 p.

Heede, B.H., 1971, Characteristics and Processes of Soil Piping in Gullies. Fort Collins, Colorado, U.S. Department of Agriculture Forest Service Research Paper RM–68, Rocky Mountain Forest and Range Experiment Station, 15 p.

Hereford, R., 1984, Climate and ephemeral-stream processes: Twentieth-century geomorphology and alluvial stratigraphy of the Little Colorado River, Arizona. Geological Society of America Bulletin, v. 95, p. 654–668, doi:10.1130/0016-7606(1984)95<654:CAEPTG>2.0.CO;2.

Hereford, R., 2002, Valley-fill alluviation during the Little Ice Age (ca. A.D. 1400–1880), Paria River basin and southern Colorado Plateau, United States. Geological Society of America Bulletin, v. 114, p. 1550–1563, doi:10.1130/0016-7606(2002)114<1550:VFADTL>2.0.CO;2.

Hereford, R., Jacoby, G.C., and McCord, V.A.S., 1996, Late Holocene Alluvial Geomorphology of the Virgin River in the Zion National Park Area, Southwest Utah. Geological Society of America Special Paper 310, 41 p.

Hupp, C.R., 1992, Riparian vegetation recovery patterns following stream channelization: A geomorphic perspective. Ecology, v. 73, p. 1209–1226, doi:10.2307/1940670.

Jackson, W.H., 1878, Report on the Ancient Ruins Examined in 1877. Washington, D.C., 10th Annual Report, U.S. Geologic and Geographic Survey of Territories for the Year 1876, 42 p.

Kang, S., and Sotiropoulos, F., 2011, Flow phenomena and mechanisms in a field-scale experimental meandering channel with a pool-riffle sequence: Insights gained via numerical simulation. Journal of Geophysical Research, v. 116, p. F03011, doi:10.1029/2010JF001814.

Karlstrom, E.T., and Karlstrom, T.N.V., 1987, Late Quaternary alluvial history of the American West: Toward a process paradigm. Geology, v. 15, p. 88–89, doi:10.1130/0091-7613(1987)15<88:LQAHOT>2.0.CO;2.

Kean, J.W., and Smith, J.D., 2004, Flow and boundary shear stress in channels with woody bank vegetation, *in* Bennett, S., and Simon, A., eds., Riparian Vegetation and Fluvial Geomorphology. American Geophysical Union Water Science and Application Monograph 8, p. 237–252.

Knox, J.C., 1977, Human impacts on Wisconsin stream channels. Annals of the Association of American Geographers, v. 67, p. 323–342, doi:10.1111/j.1467-8306.1977.tb01145.x.

Love, D.W., 1980, Quaternary Geology of Chaco Canyon, New Mexico [Ph.D. dissertation]. Albuquerque, New Mexico, University of New Mexico, 613 p.

Love, D.W., 1986, A geological perspective of sediment storage and delivery along the Rio Puerco, central New Mexico, *in* Hadley, R.F., ed., Drainage Basin Sediment Delivery. Institute of Hydrology International Association of Hydrological Sciences Publication 159, p. 305–322.

Love, D.W., 1997, Historic incision of the middle Rio Puerco of the east: Implications for models of arroyo entrenchment and distribution of archaeological sites, *in* Duran, M.S., and Kirkpatrick, D.T., eds., Layers of Time: Papers in Honor of Robert H. Weber. Archaeological Society of New Mexico, Papers in Honor, v. 23, p. 69–84.

Love, D.W., and Young, J.D., 1983, Progress Report on the Late Cenozoic Geologic Evolution of the Lower Rio Puerco, *in* Chapin, C.E., ed., Socorro Region II. Socorro, New Mexico, New Mexico Geological Society, 34th Field Conference Guidebook, p. 277–284.

Mann, D.H., and Meltzer, D.J., 2007, Millennial-scale dynamics of valley fills over the past 12,000 ^{14}C yr in northeastern New Mexico, USA. Geological Society of America Bulletin, v. 119, p. 1433–1448, doi:10.1130/B26034.1.

Mehl, A.E., and Zárate, M.A., 2012, Late Quaternary alluvial records and environmental conditions in the eastern Andean piedmont of Mendoza (33–34°S, Argentina). Journal of South American Earth Sciences, v. 37, p. 41–59, doi:10.1016/j.jsames.2012.01.003.

Molnar, P., and Ramirez, J.A., 2001, Recent trends in precipitation and streamflow in the Rio Puerco Basin. Journal of Climate, v. 14, p. 2317–2328, doi:10.1175/1520-0442(2001)014<2317:RTIPAS>2.0.CO;2.

Nanson, G.C., and Beach, H.F., 1977, Forest succession and sedimentation on a meandering-river floodplain, northeast British Columbia, Canada. Journal of Biogeography, v. 4, p. 229–251, doi:10.2307/3038059.

National Park Service, 1934, Chaco Canyon National Monument Topographical Sheets. San Francisco, California, Office of the Chief Engineer, scale 1:480, 42 sheets.

New Mexico State Engineer, 1930, Ninth Biennial Report. Santa Fe, New Mexico, New Mexico State Engineer, p. 244–288.

Nordin, C.F., Jr., 1963, A Preliminary Study of Sediment Transport Parameters, Rio Puerco near Bernardo, New Mexico. U.S. Geological Survey Professional Paper 462-C, p. 1–21.

Nordin, C.F., Jr., and Curtis, W.F., 1962, Formation and Deposition of Clay Balls, Rio Puerco, New Mexico. U.S. Geological Survey Professional Paper 540-B, article 14, p. 37–40.

Osterkamp, W.R., and Friedman, J.M., 2000, The disparity between extreme rainfall events and rare floods—With emphasis on the semi-arid American West. Hydrological Processes, v. 14, p. 2817–2829, doi:10.1002/1099-1085(200011/12)14:16/17<2817::AID-HYP121>3.0.CO;2-B.

Patton, P.C., and Schumm, S.A., 1981, Ephemeral-stream processes: Implications for studies of Quaternary valley fills. Quaternary Research, v. 15, p. 24–43, doi:10.1016/0033-5894(81)90112-5.

Perignon, M.C., Tucker, G.E., Griffin, E.R., and Friedman, J.M., 2013, Effects of riparian vegetation on topographic change during a large flood event, Rio Puerco, New Mexico, USA. Journal of Geophysical Research–Earth Surface, v. 118, p. 1193–1209.

Pollen-Bankhead, N., Simon, A., Jaeger, K., and Wohl, E., 2009, Destabilization of streambanks by removal of invasive species in Canyon de Chelly National Monument, Arizona. Geomorphology, v. 103, p. 363–374, doi:10.1016/j.geomorph.2008.07.004.

Prosser, I.P., Rutherfurd, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J., and Moran, C.J., 2001, Large-scale patterns of erosion and sediment transport in river networks, with examples from Australia. Marine & Freshwater Research, v. 52, p. 81–99, doi:10.1071/MF00033.

Sancho, C., Peña, J.L., Muñoz, A., Benito, G., McDonald, E., Rhodes, E.J., and Longares, L.A., 2008, Holocene alluvial morphopedosedimentary record and environmental changes in the Bardenas Reales Natural Park (NE Spain). Catena, v. 73, p. 225–238, doi:10.1016/j.catena.2007.09.011.

Schumm, S.A., and Hadley, R.F., 1957, Arroyos and the semiarid cycle of erosion. American Journal of Science, v. 255, p. 161–174, doi:10.2475/ajs.255.3.161.

Schumm, S.A., and Parker, R.S., 1973, Implications of complex response of drainage systems for Quaternary alluvial stratigraphy. Nature–Physical Science (London), v. 243, p. 99–100, doi:10.1038/physci243099a0.

Shafroth, P.B., Cleverly, J.R., Dudley, T.L., Taylor, J.P., Van Riper, C., III, Weeks, E.P., and Stuart, J.N., 2005, Control of *Tamarix* in the western United States: Implications for water salvage, wildlife use, and riparian restoration. Environmental Management, v. 35, p. 231–246, doi:10.1007/s00267-004-0099-5.

Sigafoos, R.S., 1964, Botanical Evidence of Floods and Flood-Plain Deposition. U.S. Geological Survey Professional Paper 485-A, 35 p.

Simon, A., 1989, A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms, v. 14, p. 11–26, doi:10.1002/esp.3290140103.

Simon, A., and Collison, A.J.C., 2002, Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms, v. 27, p. 527–546, doi:10.1002/esp.325.

Simpson, J.H., 1850, Journal of a Military Reconnaissance from Santa Fe, New Mexico, to the Navajo Country in 1849. Report of the Secretary of War, 31st Congress, 1st Session, Senate Ex. Doc. No. 64, p. 56–168.

Smith, J.D., and McLean, S.R., 1984, A model for flow in meandering streams. Water Resources Research, v. 20, p. 1301–1315, doi:10.1029/WR020i009p01301.

Stokes, M.A., and Smiley, T.L., 1968, An Introduction to Tree-Ring Dating. Tucson, Arizona, University of Arizona Press, 73 p.

Thornthwaite, C.W., Sharpe, C.F.S., and Dosch, E.F., 1942, Climate and Accelerated Erosion in the Arid and Semiarid Southwest, with Special Reference to the Polacca Wash Drainage Basin, Arizona. U.S. Department of Agriculture Technical Bulletin 808, 134 p.

Trimble, S.W., 1999, Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975–93. Science, v. 285, p. 1244–1246, doi:10.1126/science.285.5431.1244.

Tuan, Y.F., 1966, New Mexican gullies: A critical review and some recent observations. Annals of the Association of American Geographers, v. 56, p. 573–597, doi:10.1111/j.1467-8306.1966.tb00581.x.

Tucker, G.E., Arnold, L., Bras, R.L., Flores, H., Istanbulluoglu, E., and Solyom, P., 2006, Headwater channel dynamics in semiarid rangelands, Colorado High Plains, USA. Geological Society of America Bulletin, v. 118, p. 959–974, doi:10.1130/B25928.1.

U.S. Geological Survey, 2012, National Water Information System (NWISWeb). http://waterdata.usgs.gov/nwis/ (accessed June 2012).

U.S. Geological Survey digital data, 1999, National Atlas of the United States of America. U.S. Geological Survey, Reston, Virginia. http://nationalatlas.gov/ (accessed 27 March 2008).

Van de Wiel, M.J., and Darby, S.E., 2007, A new model to analyze the impact of woody riparian vegetation on the geotechnical stability of riverbanks. Earth Surface Processes and Landforms, v. 32, p. 2185–2198, doi:10.1002/esp.1522.

Vincent, K.R., Friedman, J.M., and Griffin, E.R., 2009, Erosional consequence of saltcedar control. Environmental Management, v. 44, p. 218–227, doi:10.1007/s00267-009-9314-8.

Vivoni, E.R., Bowman, R.S., Wyckoff, R.L., Jakubowski, R.T., and Richards, K.E., 2006, Analysis of a monsoon flood event in an ephemeral tributary and its downstream hydrologic effects. Water Resources Research, v. 42, W03404, doi:10.1029/2005WR004036.

Waters, M.R., and Haynes, C.V., 2001, Late Quaternary arroyo formation and climate change in the American Southwest. Geology, v. 29, p. 399–402, doi:10.1130/0091-7613(2001)029<0399:LQAFAC>2.0.CO;2.

Webb, R.H., Smith, S.S., and McCord, V.A.S., 1991, Historic Channel Change of Kanab Creek, Southern Utah and Northern Arizona. Grand Canyon Natural History Association Monograph 9, 91 p.

Welsh, M., 1985, The United States Corps of Engineers in the Middle Rio Grande Valley, 1935–1955. New Mexico Historical Review, v. 60, p. 295–316.

Western Regional Climate Center, 2012, NCDC 1971–2000 Monthly Normals. http://www.wrcc.dri.edu/ (accessed November 2012).

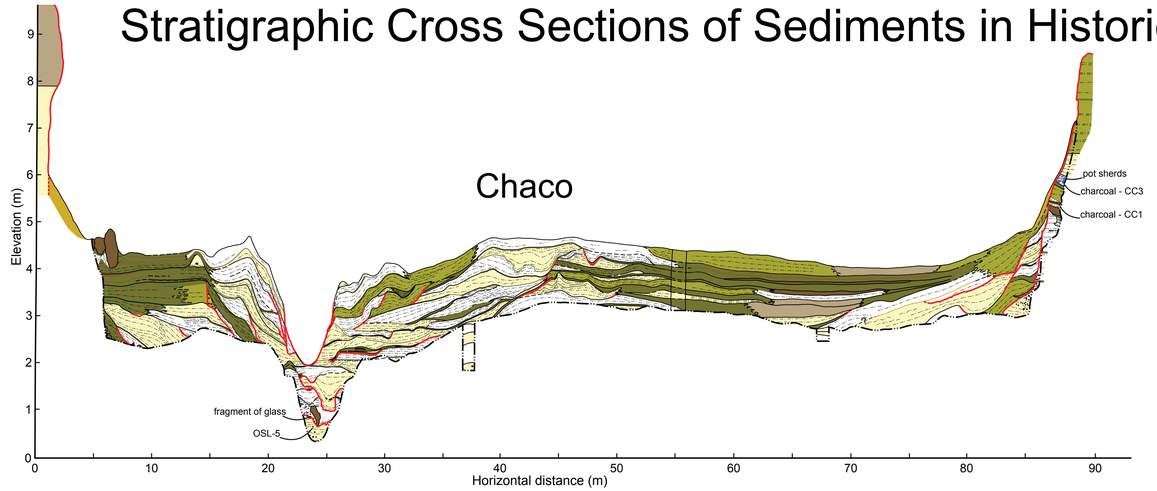
Science Editor: Christian Koeberl
Associate Editor: Joan Florsheim

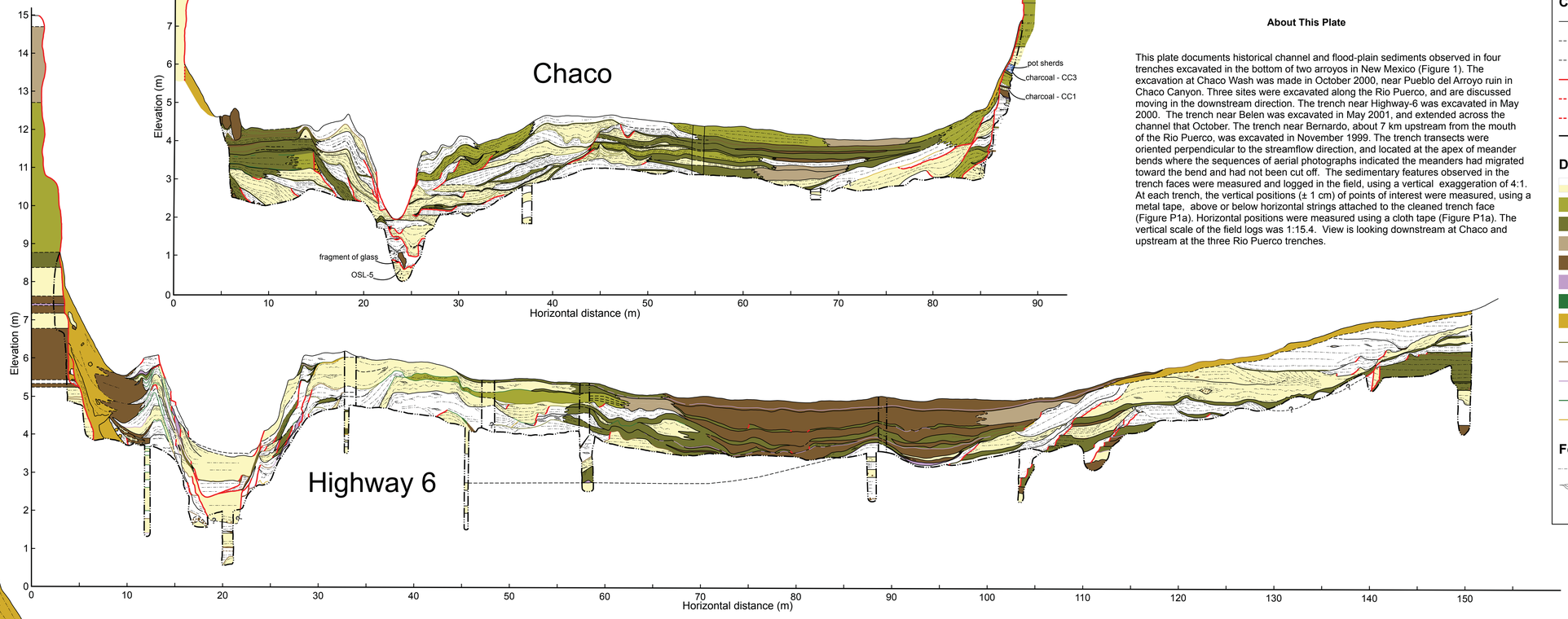
Manuscript Received 9 December 2013
Revised Manuscript Received 7 July 2014
Manuscript Accepted 6 August 2014

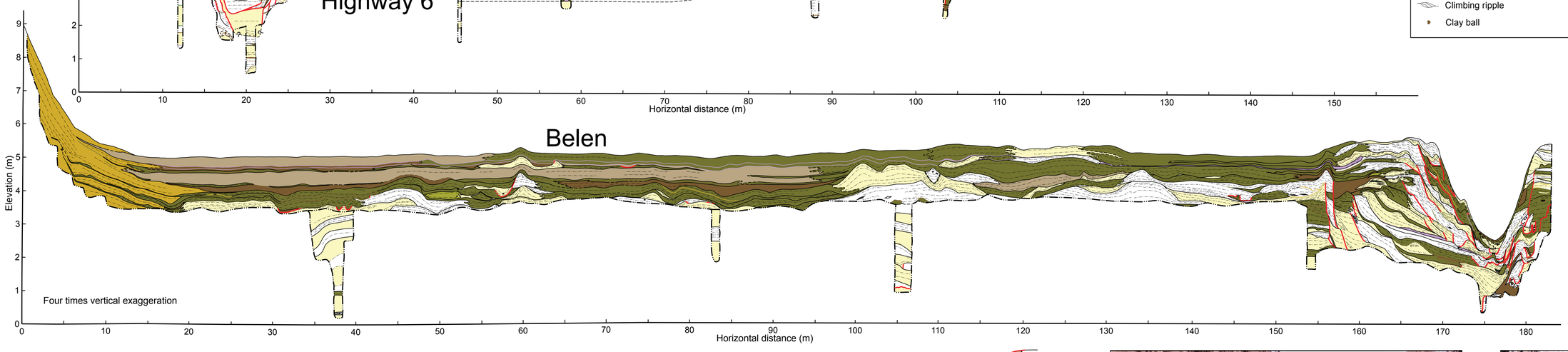
Printed in the USA

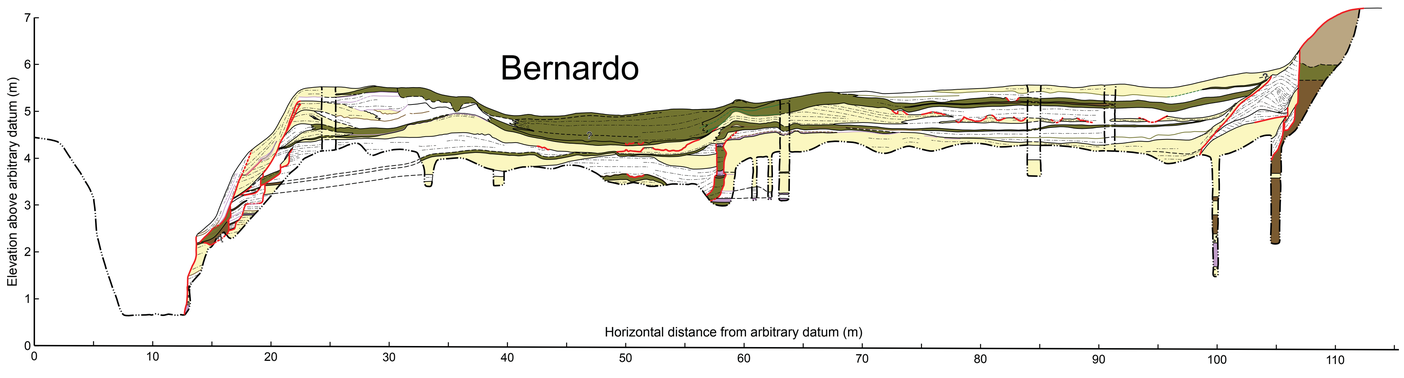
Processes of arroyo filling in northern New Mexico, USA
Jonathan M. Friedman, Kirk R. Vincent, Eleanor R. Griffin, Michael L. Scott, Patrick B. Shafroth, and Gregor T. Auble
Plate 1
Supplement to: *Geological Society of America Bulletin*, v. 127, no. 3/4; doi:10.1130/B31046.1.S1
© Copyright 2014 Geological Society of America

Stratigraphic Cross Sections of Sediments in Historical Arroyos in New Mexico









About This Plate

This plate documents historical channel and flood-plain sediments observed in four trenches excavated in the bottom of two arroyos in New Mexico (Figure 1). The excavation at Chaco Wash was made in October 2000, near Pueblo del Arroyo ruin in Chaco Canyon. Three sites were excavated along the Rio Puerco, and are discussed moving in the downstream direction. The trench near Highway-6 was excavated in May 2000. The trench near Belen was excavated in May 2001, and extended across the channel that October. The trench near Bernardo, about 7 km upstream from the mouth of the Rio Puerco, was excavated in November 1999. The trench transects were oriented perpendicular to the streamflow direction, and located at the apex of meander bends where the sequences of aerial photographs indicated the meanders had migrated toward the bend and had not been cut off. The sedimentary features observed in the trench faces were measured and logged in the field, using a vertical exaggeration of 4:1. At each trench, the vertical positions (± 1 cm) of points of interest were measured, using a metal tape, above or below horizontal strings attached to the cleaned trench face (Figure P1a). Horizontal positions were measured using a cloth tape (Figure P1a). The vertical scale of the field logs was 1:15.4. View is looking downstream at Chaco and upstream at the three Rio Puerco trenches.

Explanation of Map Units

Contacts

- Depositional contact
- Depositional contact, approximate
- Depositional contact, inferred
- Erosional contact
- Erosional contact, approximate
- Erosional contact, inferred
- Bottom or edge of trench

Deposits

- Sand bed: deposits alternate between white & yellow
- Interbedded sand and silt
- Silt bed
- Interbedded silt and clay
- Clay
- Marker bed of purple, red, pink, or orange sediment
- Silt with leaf litter
- Colluvium and wind-blown sand
- Silt lamina
- Clay lamina
- Marker lamina of pink-colored silt, dashed where approximate
- Silt lamina with leaf litter, dashed where approximate
- Marker lamina of orange silt, dashed where approximate

Features Within Beds

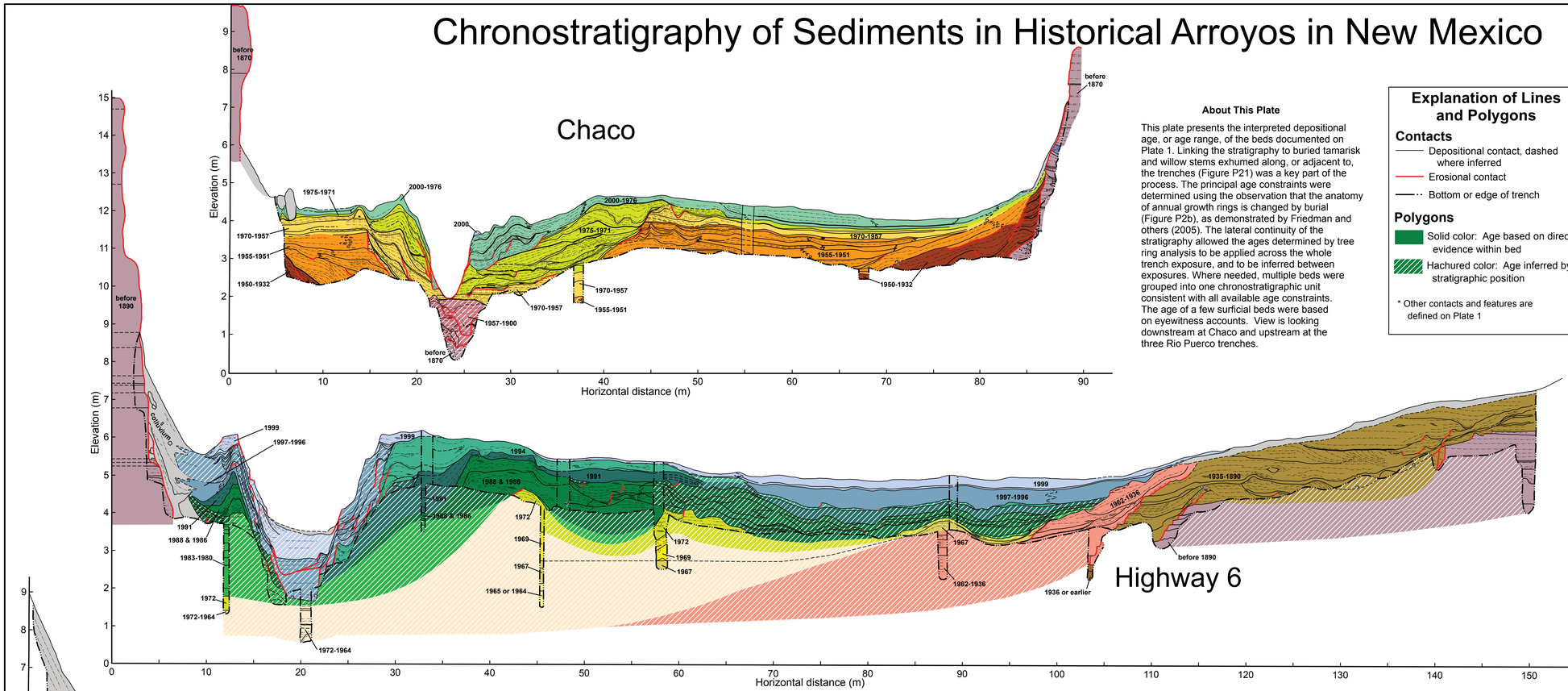
- Stratification within bed
- Climbing ripple
- Clay ball

Figure P1a: View of Chaco Wash deposits looking from horizontal distance 65 toward the arroyo wall. The height of the exposed trench face is 1.4 m.

Figure P1b: Stratification of sand deposits at levee crest. The horizontal pink pencil at lower left is 12 cm long.

Processes of arroyo filling in northern New Mexico, USA
Jonathan M. Friedman, Kirk R. Vincent, Eleanor R. Griffin, Michael L. Scott, Patrick B. Shafroth, and Gregor T. Auble
Plate 2
Supplement to: *Geological Society of America Bulletin*, v. 127, no. 3/4; doi:10.1130/B31046.1.S1
© Copyright 2014 Geological Society of America

Chronostratigraphy of Sediments in Historical Arroyos in New Mexico



About This Plate

This plate presents the interpreted depositional age, or age range, of the beds documented on Plate 1. Linking the stratigraphy to buried tamarisk and willow stems exhumed along, or adjacent to, the trenches (Figure P21) was a key part of the process. The principal age constraints were determined using the observation that the anatomy of annual growth rings is changed by burial (Figure P2b), as demonstrated by Friedman and others (2005). The lateral continuity of the stratigraphy allowed the ages determined by tree ring analysis to be applied across the whole trench exposure, and to be inferred between exposures. Where needed, multiple beds were grouped into one chronostratigraphic unit consistent with all available age constraints. The age of a few surficial beds were based on eyewitness accounts. View is looking downstream at Chaco and upstream at the three Rio Puerco trenches.

Explanation of Lines and Polygons

Contacts

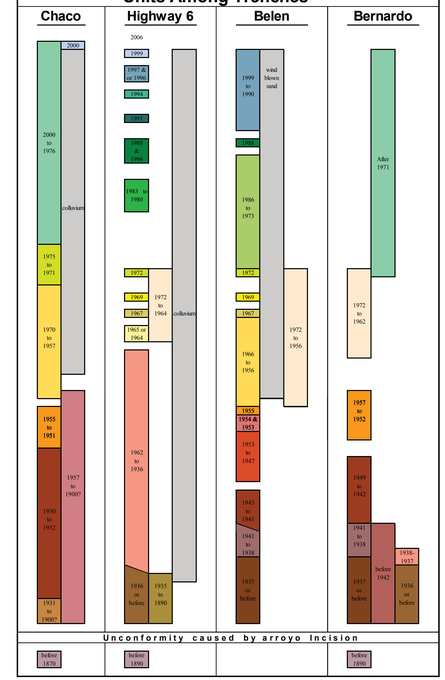
- Depositional contact, dashed where inferred
- Erosional contact
- Bottom or edge of trench

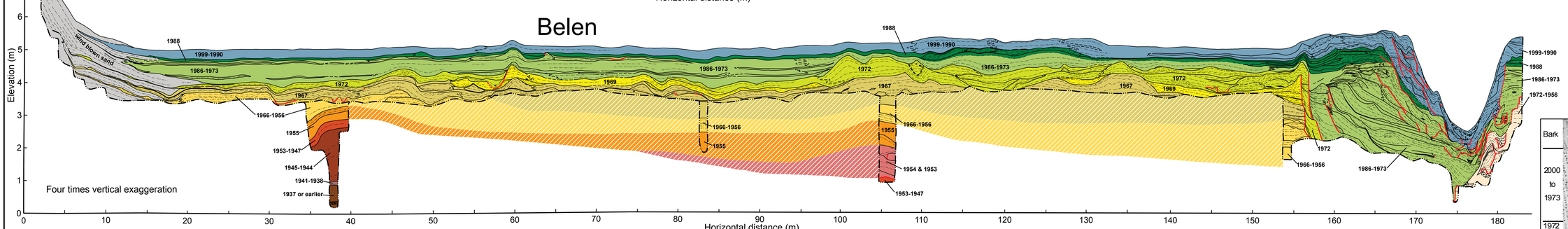
Polygons

- Solid color: Age based on direct evidence within bed
- Hachured color: Age inferred by stratigraphic position

* Other contacts and features are defined on Plate 1

Correlation of Chronostratigraphic Units Among Trenches





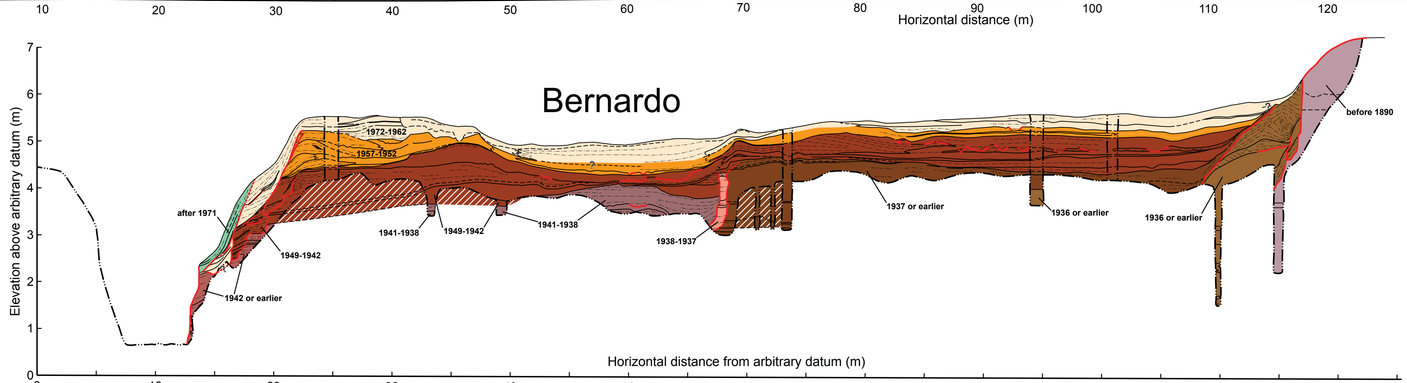


Figure P2a: Excavated tamarisk that germinated in 1944, at 1.7 m below the present ground surface, along Chaco Wash at a horizontal distance of 6 m along the trench. Because burial suppresses lateral growth, stem diameter decreases with increasing depth. The aluminum tags on the stems mark the position of stratigraphic contacts that allowed tree ring evidence of burial to be linked to the stratigraphy.

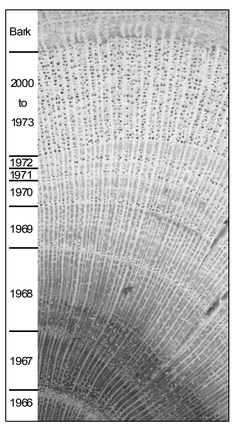


Figure P2b: Tamarisk stem cross-section cut 2.8 m below the ground surface in 2000. Following initial burial of 68 cm of sediment in 1969, ring-width decreased, vessel size increased, and annual transitions became less distinct. After a second burial by 41 cm of sediment in 1972, annual transitions became indistinguishable. The color change from dark to light within the 1968 ring is unrelated to burial.