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CONTRIBUTIONS OF MODERATELY LOW FLOWS AND LARGE FLOODS TO GEOMORPHIC CHANGE IN THE RIO PUERCO ARROYO, NEW MEXICO

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Abstract—From the mid-1800s to around 1930, monsoonal floods incised an arroyo roughly 100 m wide and 10 m deep along the lower Rio Puerco, NM, from the confluence with the Rio San Jose downstream to the mouth at the Rio Grande, causing sedimentation and flooding downstream. Since the 1930s, the channel has greatly narrowed, a densely vegetated floodplain has developed, the arroyo has partly filled, and downstream sedimentation has greatly decreased. Application of herbicide to a 12-km reach of the arroyo in 2003 to control non-native saltcedar (*Tamarix* spp.) prompted ongoing studies of channel change in the presence and absence of dense, riparian, woody vegetation. We used digital terrain models and satellite imagery to quantify changes in channel width and location in the sprayed reach and in an unsprayed reach downstream during a moderately low-flow interval (November 2006 to March 2010) and during an interval with a large flood (March 2010 to January/February 2014). Channel width increased in magnitude and variability in the sprayed reach but not in the unsprayed reach over both intervals, continuing a pattern first observed in an earlier study of the period 2003 to 2006. Since the herbicide application in 2003, there have been a total of five meander cutoffs in the sprayed reach and none in the unsprayed reach. In kilometer-long sections of the sprayed reach, channel width is now approaching that at the beginning of the period of channel narrowing in 1935.

INTRODUCTION

The Rio Puerco Basin, located in semiarid north-central New Mexico (Fig. 1), has long been of interest to geomorphologists, because it has delivered large and temporally variable suspended-sediment loads to the middle Rio Grande (Bryan and Post, 1927; Bryan, 1928; Nordin, 1963; Love, 1986; Elliott et al., 1999). This sediment has contributed to aggradation and flooding in the middle Rio Grande valley (Happ, 1948) and reduced storage capacity in Elephant Butte Reservoir (Bryan and Post, 1927).

The Rio Puerco is an ephemeral tributary of the Rio Grande with a contributing drainage area that is about 16,100 km^2. Elevation ranges from 3444 m at the summit of Mount Taylor, located near the center of the watershed near Cubero, to 1440 m near the mouth of the Rio Puerco at Bernardo (Fig. 1). The lower Rio Puerco is incised within fine valley-fill sediment, including sand, silt and clay, with the finer sediment providing cohesion that supports near-vertical walls (Love, 1986; Friedman et al., 2015). The Rio Puerco is one of the most intensively studied arroyos in the world (Bryan, 1928; Love, 1986; Elliot et al., 1999; Gellis et al., 2012; Friedman et al., 2015). Arroyos are deep, oversized channels usually with vertical or steeply cut walls of silt, clay or sand (Cooke and Reeves, 1976; Gellis et al., 2012), occurring in semiarid or arid regions worldwide (Friedman et al., 2015). Arroyo systems shift over the centuries between an unincised state, in which floods are attenuated across a broad floodplain, and an incised state, in which floods are trapped within a large, quasi-rectangular arroyo.

The arroyo of the Rio Puerco, roughly 200 km long, 10 m deep and 100 m wide, was incised mostly by flood erosion from the mid-1800s to early 1900s, punctuated by the flood of record, 1070 m^3/s in 1929 (Fig. 2; Bryan, 1928; Elliot et al.,

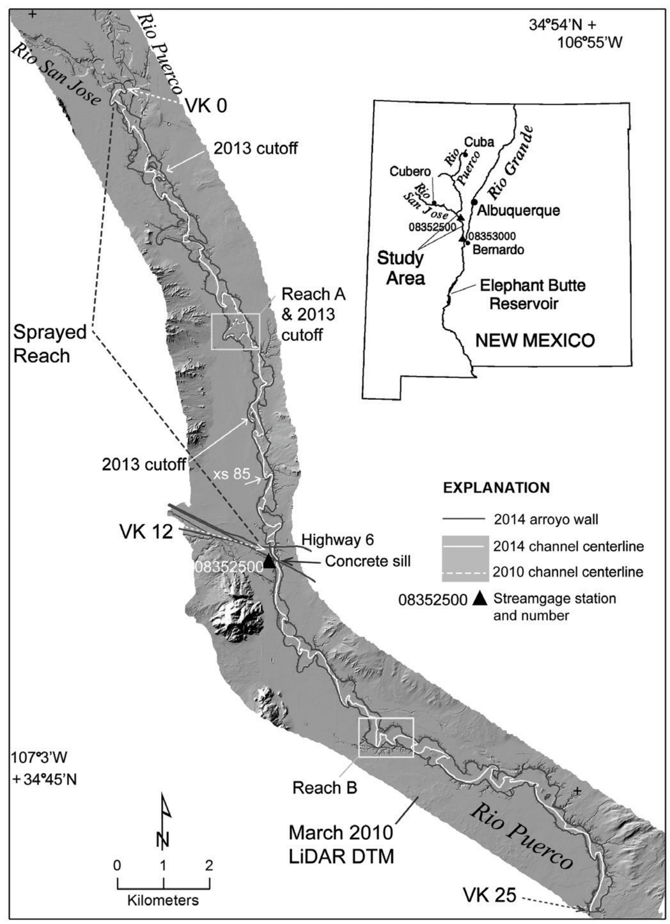

FIGURE 1. Map of the study area. Locations of three 2013 meander cutoffs in the sprayed reach are identified. Reaches A and B are highlighted in Fig. 4. "vk" indicates distance down-valley (km) from the confluence with the Rio San Jose, and "xs" represents cross section. The shaded relief image was created from March 2010 LiDAR DTMs (Perignon et al., 2013).

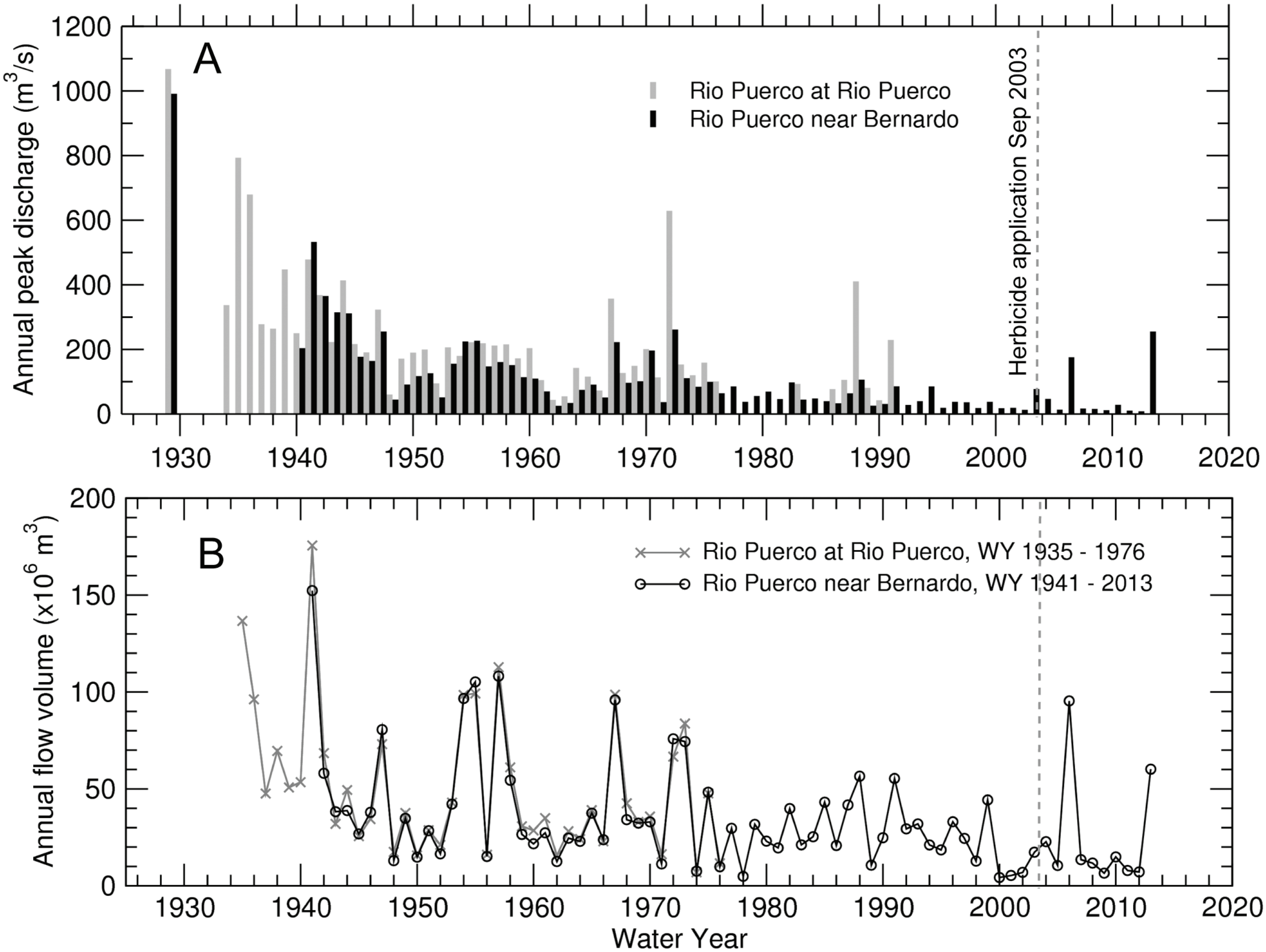

FIGURE 2. Annual peak flow discharge (**A**) and flow volume (**B**) computed for data of USGS streamgage stations Rio Puerco near Bernardo, New Mexico (#08353000), and Rio Puerco at Rio Puerco, New Mexico (#08352500). (See Fig. 1 for locations.) The 1929 peaks were estimated by the New Mexico State Engineer (1930). Streamgage data from U.S. Geological Survey (2014).

1999). In the 1930s, the arroyo bottom, 70 km downstream from the confluence with the Rio San Jose (Fig. 1), was dominated by a wide braided channel, and woody vegetation was scarce (Friedman et al., 2015). Since the 1930s, peak flows have decreased, the channel has narrowed, a densely forested floodplain has developed (Fig. 3), and the arroyo has aggraded (Elliott et al., 1999; Griffin et al., 2014; Friedman et al., 2015). The floodplain forest is dominated by the large Eurasian shrub saltcedar (*Tamarix* spp.) locally introduced in 1926 (Bryan and Post, 1927), and there is a discontinuous band of sandbar willow (*Salix exigua*) along the channel. Between 1935 and 1996, the average channel width between Highway 6 and Bernardo decreased from about 41 m to 12 m, while average shrub canopy cover increased from about 9% of the arroyo bottom to nearly 70% (Friedman et al., 2015).

Geomorphic changes in the lower Rio Puerco associated with large floods were described by Heath (1983), Perignon et al. (2013), Griffin et al. (2014), and Friedman et al. (2015). Effects of the basin sedimentology on erosion, transport and storage of sediment in stream valleys were discussed by Love (1986), who developed an estimated sediment budget for erosional and depositional features in the basin.

The lower Rio Puerco is a losing stream, with infiltration into channel bed, bank, and floodplain surfaces, and reducing peak flow magnitudes between the Highway 6 crossing and the streamgage near Bernardo (Fig. 1; Heath, 1983; Griffin et al., 2005). Long-term erosion rates in the Rio Puerco Basin were calculated by Clapp et al. (2001) and Bierman et al. (2005) using cosmogenic nuclides. Factors controlling erosion rates in the upper basin were examined by Gellis et al. (2012). Effects of drag on saltcedar stems in reducing vertically-averaged flow velocity, shear stress on the sediment surface, and sand transport in suspension across the floodplain were quantified by Griffin et al. (2014). The stability of the narrow channel inset within the arroyo and the formation of near-bank levees also were explained by Griffin et al. (2014).

Semiarid regions of the western United States are characterized by large spatial and temporal variability in precipitation

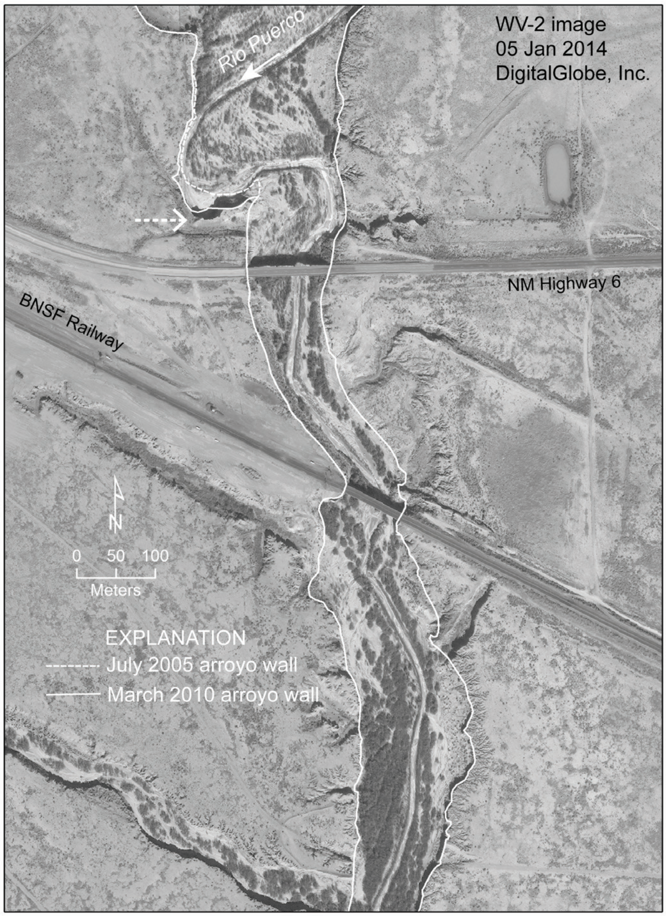

FIGURE 3. Mapped 2005 and 2010 Rio Puerco arroyo wall locations overlain on a January 2014 satellite image showing the NM Highway 6 crossing and the BNSF Railway bridge. The dashed arrow points to a site where erosion since 2005, caused by large floods in 2006 and 2013, has moved the wall about 38 m toward the highway at the apex of the bend. The downstream limit of the sprayed reach was the Highway 6 bridge. Note the difference in floodplain canopy cover (dark areas) upstream and downstream from Highway 6.

(Molnár and Ramírez, 2001). In the Rio Puerco Basin, where the surficial geology is dominated by easily eroded sedimentary rocks (Love, 1986), episodic heavy or prolonged rainfall events can cause high runoff with flash flooding, surface erosion, and the transport of high volumes of sediment in suspension (Elliott et al., 1999). Precipitation over the Rio Puerco Basin is dominantly driven by the summer/early fall monsoon that brings moisture from the Gulf of Mexico and the eastern Pacific (Molnár and Ramírez, 2001; National Weather Service (NWS), 2013a). Throughout the watershed, the months with the highest average precipitation are July through October (Molnár and Ramírez, 2001). In addition, all but two of the 25 annual peaks in the record of the streamgage near Bernardo that were above the 74-yr average (102 m^3/s, standard deviation (sd) 97 m^3/s) occurred during the monsoon months of June through October.

Riparian vegetation herbicide treatment

In September 2003, a 12-km segment of the lower Rio Puerco arroyo was sprayed with an herbicide by helicopter to remove non-native saltcedar (Fig. 1). The herbicide killed almost all of the saltcedar, which formerly grew across the floodplain, and almost all of the native sandbar willow, which formerly grew along the channel banks (Vincent et al., 2009). During a large flood in August 2006, channel width increased by an average of 84% in the sprayed reach, whereas average channel width in the downstream (untreated) reach remained the same (Vincent et al., 2009). In the sprayed reach, removal of dense, flexible woody stems from channel banks reduced fluid drag on the flow, leading to high shear stress at the toe of the banks (Kean and Smith, 2004; Griffin et al., 2010), bank undercutting, and mass failure (Vincent et al., 2009). Another large flood occurred in September 2013, and geomorphic effects of that flood were examined for this study.

Post-treatment precipitation and flow

The two recent large floods, on August 10, 2006, and on September 15, 2013, (176 and 255 m^3/s, respectively) were larger than any annual peak flows since 1972 at the streamgage near Bernardo (Fig. 2; U.S. Geological Survey (USGS), 2014). These two floods were separated by a 7-year interval of moderately low flow. The August 2006 and September 2013 floods were caused by repeated daily convective thunderstorms enhanced by surges of monsoonal moisture from the south (National Weather Service (NWS), 2006; 2013a). During August 2006 and September 2013, the weather station with the highest total precipitation within the Rio Puerco Basin was located at Cubero, NM (Fig. 1; Griffin et al., 2010; NWS, 2013b), near the center of the basin. At Cubero, total precipitation from Aug. 3-10, 2006, was 129 mm, nearly half of the average annual precipitation (270 mm, n = 31 years, 1977–2013). From Sept. 10-15, 2013, precipitation at Cubero totaled 72 mm. Total precipitation during the months of August 2006 (163 mm) and September 2013 (84 mm) were record high totals for those months at this station for the 37 and 36 years of record, respectively (National Centers for Environmental Information, 2016). The data show that the flood peaks arrived within three days after substantial precipitation on an already saturated landscape (Griffin et al., 2010; NWS, 2013a).

Objectives

Digital terrain models developed from March 2010 aerial LiDAR data and satellite imagery from January/February 2014 provided an opportunity to assess changes in channel width and location during a moderately low-flow interval (November 2006 to March 2010) and an interval with a large flood (March 2010 to January/February 2014). We mapped channel bank locations in 2010 and 2014 through the 25-km-long study reach (Fig. 1), identified new channel areas created by meander cutoffs, and determined change in channel width as a function of distance down-valley for the two time periods. We assessed the magnitude and patterns of change in the sprayed reach compared to the downstream reach during both the moderately low-flow interval and during the 2013 flood. We placed these changes in the context of the century-scale geomorphic change reported by Vincent et al. (2009), Perignon et al. (2013), Griffin et al. (2014) and Friedman et al. (2015). Our goal was to determine to what extent the reduction in woody vegetation in the sprayed reach has affected geomorphic change within the lower Rio Puerco arroyo from November 2006 to January/February 2014.

METHODS

Data

We computed annual flow volumes from the records of daily mean discharge at the USGS streamgages Rio Puerco near Bernardo, New Mexico (#08353000) and Rio Puerco at Rio Puerco, New Mexico (#08352500). Daily mean discharge and annual peak flow data from the streamgage near Bernardo for the period November 1, 1939 – September 30, 2013 were examined (USGS, 2014). Records from the streamgage at Rio Puerco are available for Water Years (WY; year beginning October 1 and ending September 30, designated by year in which it ends) 1935–1976. Use of this streamgage was discontinued in 1976, but peak flow discharges for 1983 and 1986–1991 were estimated from peak stage above the concrete sill and flow geometry at this site (Fig. 1). Flood peak discharge estimates for 1929 at both streamgage sites were made by the New Mexico State Engineer (1930). Comparison of the relative magnitudes of annual peak discharge and annual flow volume give an indication of the flood-flow duration in each year. For example, a short-duration, high-peak flow could have a smaller flow volume than a long-duration flood with a lower magnitude peak discharge.

We mapped channel bank locations from high-resolution raster imagery using multiple criteria, described below. Digital Terrain Models (DTMs; 0.5-m cell size) derived from aerial LiDAR survey data collected in March 2010 (Perignon et al., 2013) provide high-resolution, bare-earth surfaces with horizontal accuracy of 0.10 m (National Center for Airborne Laser Mapping (NCALM), 2011). Elevations interpolated from the DTM were determined to be within 0.13 m of elevations at the same horizontal locations surveyed using high-precision GPS (Griffin et al., 2014). Shaded relief images created from the DTMs provide the most accurate base for mapping channel bank location by eye, because the abrupt change in slope from the steep channel bank to the floodplain is visible.

We mapped change in channel bank locations from March 2010 to January/February 2014 using georeferenced high-resolution (0.5-m pixel size), natural-color imagery collected by DigitalGlobe's WorldView-2 satellite (DigitalGlobe, Inc., 2014). The streamgage record indicates that there was no flow in the Rio Puerco between the dates of image acquisition on January 5 and February 26, 2014. Accuracies of channel bank locations mapped from aerial and satellite imagery are limited by image resolution (pixel size), image registration errors, and errors in identification of the top of the bank (Vincent et al., 2009; Griffin et al., 2014). Errors in identification of the location of the top of the bank in aerial and satellite imagery can occur when the bank is hidden by dense canopy or the bank has a gradual, unvegetated slope. The 2013 flood removed most channel bed and bank vegetation through the sprayed reach, and channel extent was identified by the bare surfaces and channel geomorphic features. In the downstream reach, the texture of small, dense stems on channel banks differs from the texture of mature floodplain shrubs (Griffin et al., 2014). We identified the point of transition from bare channel surface to vegetated floodplain or from small, dense stems to mature canopy as the location of the top of the bank. We estimated the accuracy of linear features mapped from the 2014 satellite imagery to be within 3 m. Using the 2010 mapped channel bank locations as a base, we mapped changes in bank location where the apparent movement was >3 m. (2010 and 2014 channel bank shapefiles provided in online data repository). All data were referenced to the UTM coordinate system, North American Datum of 1983 (NAD 83), and elevations were referenced to the North American Vertical Datum of 1988 (NAVD 88).

Computation of channel width

Average 2010 and 2014 channel widths were determined from mapped channel area and centerline length for 0.5-km arroyo intervals through the reach from the confluence with the Rio San Jose to 25-km down-valley (Fig. 1). Distances down-valley from the confluence with the Rio San Jose (valley km [vk] 0) were referenced to an identified arroyo centerline (Friedman et al., 2015) that provides a consistent distance reference through time. We compared the 2010 and 2014 0.5-km average widths to November 2006 channel width (Vincent et al., 2009) to determine changes between November 2006 and March 2010, a moderately low-flow interval, and between March 2010 and January/February 2014, which included the September 2013 flood. Repeat surveys of channel cross sections conducted in January 2007, April 2010 and April 2014 using high-precision GPS (Vincent et al., 2009; Griffin et al., 2014) provided additional data for verification of change in channel width, and they provided evidence of channel and floodplain aggradation and channel movement. Data from repeat surveys of a single cross section (xs 85, Fig. 1) located at the apex of a sharp bend eroding into the arroyo wall (vk 10.04, Fig. 1) are shown in the Results and Discussion section below to illustrate geomorphic change observed from January 2007 to April 2014 in the sprayed reach. We also determined reach-average channel widths for the 12-km-long sprayed reach and 13-km-long downstream reach and compared those to July 2005 and November 2006 reach-average channel widths determined by Vincent et al. (2009).

Meander cutoff assessment

The stability of channel banks and floodplain surfaces have been shown to be strongly dependent on the density and distribution of woody bank and floodplain vegetation (Smith, 2004; Vincent et al., 2009; Griffin et al., 2014). Therefore, we identified locations of meander cutoffs that occurred during the 2013 flood and performed a qualitative assessment of differences in canopy cover at sites of cutoffs in the sprayed reach compared to sites where meander cutoffs would have been expected in the downstream reach. Examples are shown below for Reaches A and B (Fig. 1).

RESULTS AND DISCUSSION

Streamflow during the interval between the August 2006 and September 2013 floods was moderately low, with the largest annual peak discharge near Bernardo being 28.6 m^3/s on August 5, 2010. Annual flow volumes for WY 2007 through 2012 were less than the 73-yr average (34.6 x 10^6 m^3, sd 28.7 x 106 m^3, 1941-2013; Fig. 2). We know that flow losses to infiltration typically decrease the magnitude of the peaks in the downstream direction (Griffin et al., 2005). Therefore, the August 2010 peak flow may have been above bankfull near Highway 6 (about 25 m^3/s; Griffin et al., 2005). Although minor overbank flow (<10 cm deep) may have occurred in the study reach during this interval, boundary shear stresses were not sufficient to erode floodplain surfaces, and no meander cutoffs were formed. During the mapping interval from November 2006 to March 2010, annual peak discharge did not exceed 17 m^3/s (about 2/3 bankfull near Highway 6; Griffin et al., 2005), and daily mean discharge did not exceed 10.2 m^3/s. Therefore, channel change observed in this interval was caused by in-channel flow. During the mapping interval from March 2010 to January/February 2014, only the September 2013 flood was of sufficient magnitude and duration to erode floodplain surfaces and cause meander cutoffs.

Mapping of 2010 and 2014 channel bank locations revealed three meander cutoffs in the sprayed reach caused by the September 2013 flood (Figs. 1 and 4). These cutoffs are in addition to two that occurred in the sprayed reach during the 2006 flood (Vincent et al., 2009). There were no meander cutoffs formed in the downstream (unsprayed) reach during either the 2006 or 2013 floods. A comparison of vegetation canopy in the sprayed reach with typical canopy in the unsprayed downstream reach (Fig. 4) shows the persistent effects of aerial spraying of herbicide in 2003. Shrub canopy on 2014 floodplain surfaces in the sprayed reach (Fig. 4A) was considerably sparser than in the downstream reach (Fig. 4B).

The extent and density of floodplain canopy cover in the downstream reach (Fig. 4B) were similar to that in the untreated reach of Griffin et al. (2014). Results from the application of a model for flow over a shrub-covered floodplain (Smith, 2004) showed that shrub density in the untreated reach was sufficient to reduce vertically-averaged floodplain-flow velocity by an order of magnitude and to reduce the boundary shear stress on the sediment surface by two orders of magnitude during the 2006 flood (Griffin et al., 2014). Smith (2004) showed that, for similar shrub density, increasing discharge will cause an increase in flow depth, but mean flow velocity and boundary shear stress will remain low. Therefore, during the 2013 flood, drag on woody floodplain stems protected the floodplain surfaces in the untreated reach from erosion. In the sprayed reach, large gaps between floodplain shrubs provided open flow paths in which the high-velocity flow and boundary shear stress developed. The 2013 flood was of sufficient magnitude and duration to erode a new 40-m-wide and 240-m-long channel segment across the floodplain at about vk 6.5 (Fig. 4A). In the downstream reach, visible surface erosion was caused by higher-velocity flow forced between the shrub patch and base of the north arroyo wall (Fig. 4B). However, drag on nearby stems and friction along the arroyo wall reduced the mean velocity and boundary shear stress along that path sufficiently to prevent formation of a new cutoff channel.

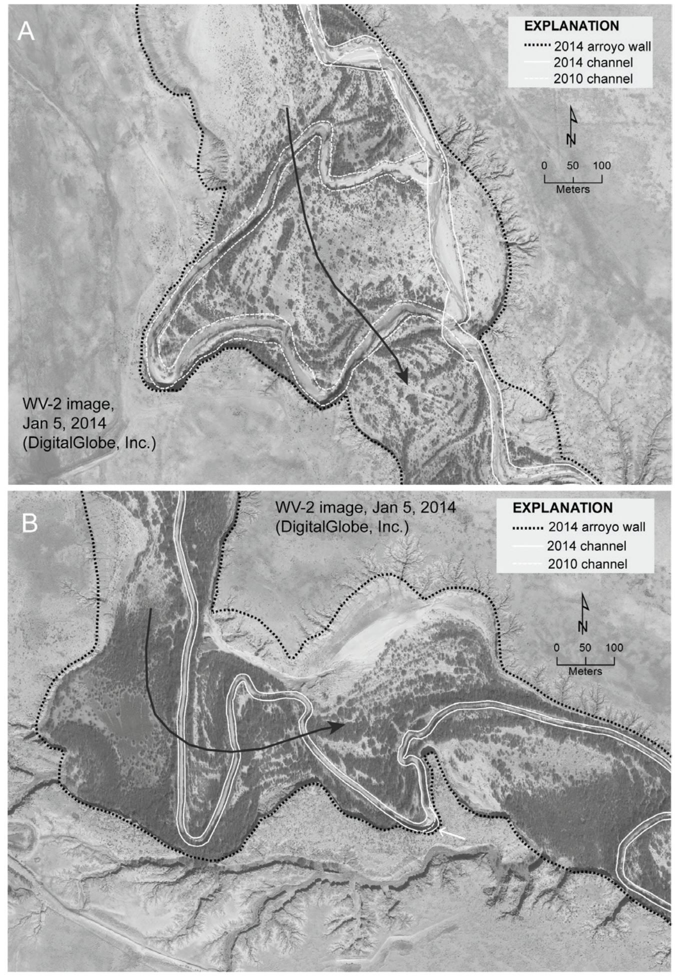

FIGURE 4. Comparison of sprayed reach segment (vk 6 – 7.3; **A**), showing a 2013 meander cutoff channel, and a highly-sinuous segment of the unsprayed downstream reach (vk 16.6 – 18.0; **B**). The solid black lines with arrows indicate down-valley flow direction, and the small white arrow in B points to a site of arroyo wall erosion.

Geomorphic change during moderately low flows

Changes in channel width in the sprayed reach after November 2006 include both widening and narrowing (Fig. 5; supplemental online data Table S1). From November 2006 to March 2010, during an interval of moderately low flows, channel banks in the sprayed reach continued to erode in some areas, and average channel width increased by >4 m in 8 of the 0.5-km arroyo intervals (33%). Erosion of channel bank and near-bank floodplain sediment between vk 5.5 and 8.0, including fine to very fine sand, increased the supply of sand

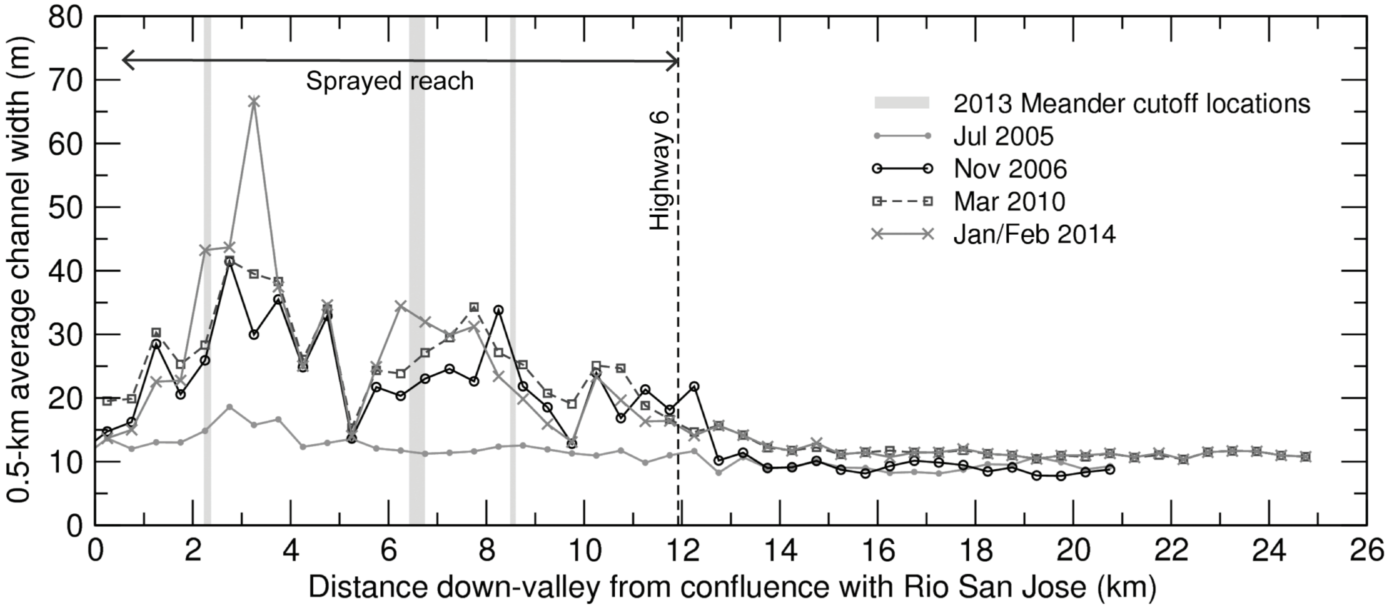

FIGURE 5. Average channel width in 0.5-km arroyo segments, showing change through time from July 2005 to January/February 2014. Data points are plotted at the center of each 0.5-km segment.

available for transport and deposition downstream. At xs 85, vk 10.04 (Fig. 6; supplemental online data Tables S2-S5), deposition on the bed and point bar surface between January 2007 and March 2010 contributed to bed aggradation. Average channel width decreased by >4 m only in the 0.5-km interval centered at vk 8.25. Change in average width was <4 m in the remaining 15 segments (63% of the reach). These changes resulted in a 12-km reach-average increase in width by about 12% between November 2006 and March 2010 (Table 1). Variability in channel width remained about the same as that in 2006. We found no detectable change in channel width in the downstream reach. Although the data suggest that channel width increased on average by about 2.4 m (Table 1), channel width mapped from imagery in Rio-Puerco reaches with dense channel bank and floodplain canopy tends to be underestimated by about 2 m on average (Vincent et al., 2009). Thus, the difference between channel width mapped in the downstream reach from November 2006 imagery and that mapped from the March 2010 DTM shaded relief image is considered to be within the error of mapping from imagery.

Geomorphic change caused by a large flood

Changes in channel width in the sprayed reach caused by the September 2013 flood (Fig. 5; Table S1) included >4 m of widening in four (17%) of the 0.5-km intervals. Erosion of channel bank and near-bank floodplain sediment in three of these segments widened the channel by >10 m on average. Average channel width increased by 15 m (54%) at vk 2.0 – 2.5, the site of the first cutoff, and by 27 m (68%) at vk 3.0 – 3.5, dominantly by lateral erosion of channel banks (see shapefiles in the online data repository). At vk 6.5, also in the vicinity of a meander cutoff (Fig. 4A), average channel width increased by about 10.6 m (45%) between March 2010 and January 2014.

TABLE 1. Rio Puerco reach-average channel widths determined from imagery and LiDAR DTMs.

	Sprayed reach (vk 0-12)			Downstream reach (vk 12.5-25)		
Imagery Date	Average width (m)	sd (m)	n	Average width (m)	sd (m)	n
July 2005*	12.7	1.99	24	9.2	0.80	17
Nov 2006*	23.5	7.24	24	9.2	0.97	17
Mar 2010	26.4	7.11	24	11.6	1.14	25
Jan/Feb 2014	26.6	12.50	24	11.6	1.17	25

vk indicates distance (km) down-valley from the confluence with the Rio San Jose.
sd indicates standard deviation.
* Modified from Vincent et al., 2009, where sprayed reach extent was vk 0 – 12.5 (n = 25), and downstream reach extent was vk 12.5 – 21.0.

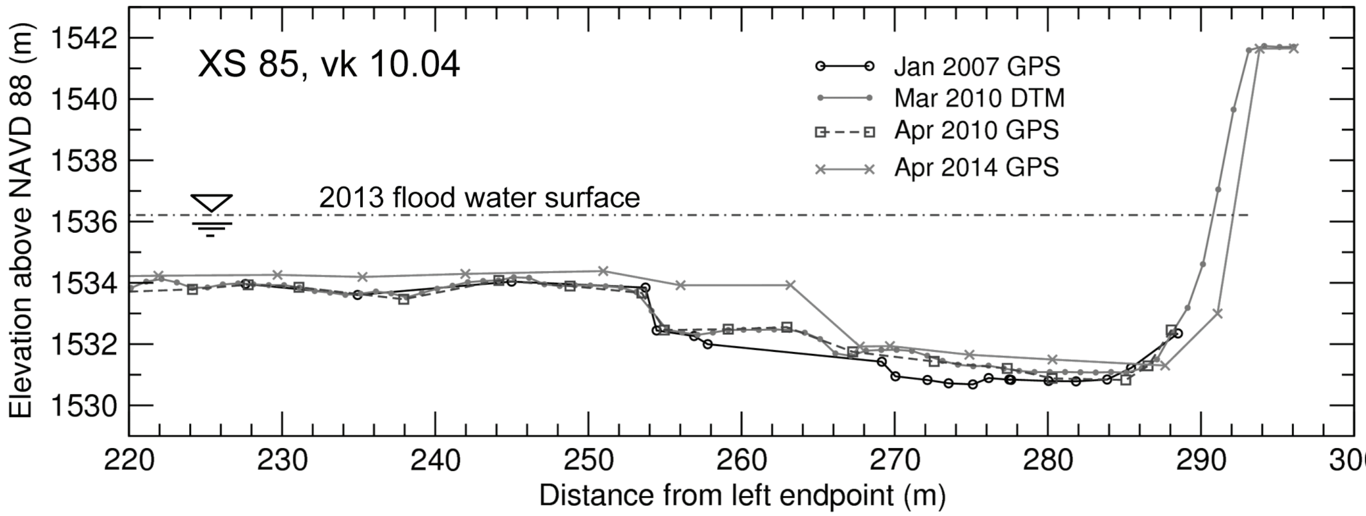

FIGURE 6. Looking downstream at cross section 85, vk 10.04, at the apex of a sharp bend in the sprayed reach. The March 2010 DTM profile is in good agreement with the April 2010 GPS survey data, and it shows erosion of the arroyo wall between March 2010 and April 2014. The 2013 flood water-surface elevation was estimated from GPS-surveyed high-water marks.

Extensive bank erosion in the first 4 km downstream from the confluence with the Rio San Jose made available fine to very fine sand for transport and deposition downstream. The increased sand load decreased the capacity of the flow for erosion downstream because the upward turbulent diffusion of sediment was balanced by the downward settling of sand already in suspension (Graf, 1971; Yalin, 1972). In the lower 4 km of the sprayed reach (vk 8 – 12), the channel narrowed on average in each interval, including at xs 85 (Fig. 6). Although the sprayed-reach average channel width increased only slightly (<1%), variability in channel width increased by about 76%. Channel top width at xs 85 was reduced from 62 m in January 2007 and April 2010 to 28 m in April 2014 by sediment deposition (dominantly sand) on the point bar. Downstream from the sprayed reach, average channel width and variability in width did not change during the 2013 flood.

CONCLUSIONS

These results show that there were substantial changes in channel width through the sprayed reach during both the interval of moderately low flow, from November 2006 to March/April 2010, and during the large flood of September 2013. Bank erosion in several segments of the sprayed reach increased 0.5-km average channel widths in 2010 and 2014 to the 1935 reach average of 41 m (Friedman et al., 2015), whereas average channel width in the downstream reach did not change in response to either the 2006 or 2013 floods. Three additional meander cutoffs during the 2013 flood show the continued vulnerability of floodplain surfaces in the sprayed reach to erosion caused by reduced presence of woody vegetation. The combined effects of the aerial spraying of herbicide in 2003 and the large flood in August 2006 destabilized the channel in the sprayed reach. The geomorphic responses in the sprayed reach to moderately low flows and a large flood suggest that sediment dynamics in the destabilized channel were similar to those during the early 1900s phase of channel and arroyo widening, before the establishment of woody vegetation within the incised arroyo. These results suggest that prior to the widespread establishment of saltcedar across the arroyo bottom, even moderately low channel flows were important agents of geomorphic change within the Rio Puerco arroyo.

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Supplemental data can be found at http://nmgs.nmt.edu/repository/index.cfml?rid=2016006