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# Erosional Consequence of Saltcedar Control

**Kirk R. Vincent · Jonathan M. Friedman ·
Eleanor R. Griffin**

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**Abstract** Removal of nonnative riparian trees is accelerating to conserve water and improve habitat for native species. Widespread control of dominant species, however, can lead to unintended erosion. Helicopter herbicide application in 2003 along a 12-km reach of the Rio Puerco, New Mexico, eliminated the target invasive species saltcedar (*Tamarix* spp.), which dominated the floodplain, as well as the native species sandbar willow (*Salix exigua* Nuttall), which occurred as a fringe along the channel. Herbicide application initiated a natural experiment testing the importance of riparian vegetation for bank stability along this data-rich river. A flood three years later eroded about 680,000 m$^3$ of sediment, increasing mean channel width of the sprayed reach by 84%. Erosion upstream and downstream from the sprayed reach during this flood was inconsequential. Sand eroded from channel banks was transported an average of 5 km downstream and deposited on the floodplain and channel bed. Although vegetation was killed across the floodplain in the sprayed reach, erosion was almost entirely confined to the channel banks. The absence of dense, flexible woody stems on the banks reduced drag on the flow, leading to high shear stress at the toe of the banks, fluvial erosion, bank undercutting, and mass failure. The potential for increased erosion must be included in consideration of phreatophyte control projects.

**Keywords** Bank stability · Erosion · LIDAR · Phreatophyte removal · Saltcedar control · Sediment transport

## Introduction

Riparian ecosystems are an important resource worldwide, providing unique habitat for plants and animals, enhancement of water quality, fuel and construction materials, and opportunities for recreation (Naiman and others 2005). These ecosystems have been damaged by flow regulation, deforestation, grazing, and introduced species (Brinson and others 1981; Richardson and others 2007). Introduced plants may degrade habitat for native species, increase water consumption, alter channel geometry and stability, and interfere with recreation (D'Antonio and Meyerson 2002; Shafroth and others 2008). Because of the great value of riparian ecosystems, their restoration is a natural resource management priority globally, and these efforts often focus on removal of nonnative woody species by mechanical, chemical or biological means (Shafroth and others 2005; Holmes and others 2005; Richardson and others 2007). To minimize negative consequences such as destabilization of stream banks and killing of nontarget species by herbicides and biological control agents, such restoration activities must be carefully designed (Holmes and others 2005; Shafroth and others 2008).

### Saltcedar Control

The most prevalent introduced riparian trees in the western United States are saltcedar (*Tamarix chinensis*, *T.*

K. R. Vincent · E. R. Griffin (✉)
U.S. Geological Survey, WRD, BRR-CR, 3215 Marine Street,
Suite E-127, Boulder, CO 80303, USA
e-mail: egriffin@usgs.gov

K. R. Vincent
e-mail: kvincent28@mac.com

J. M. Friedman
U.S. Geological Survey, Fort Collins Science Center, 2150
Centre Avenue, Building C, Fort Collins, CO 80526, USA
e-mail: freidmanj@usgs.gov

*ramosissima* and hybrids) (Gaskin and Schaal 2002) and Russian olive (*Elaeagnus angustifolia* L.) (Katz and Shafroth 2003). These species have become the second and fifth most abundant lowland riparian trees in the interior western United States (Friedman and others 2005a), occupying several hundred thousand hectares (Zavaleta 2000). Managers are increasingly removing saltcedar and Russian-olive in order to reduce water lost to evapotranspiration, improve wildlife habitat, or restore native vegetation (Zavaleta 2000; Hart and others 2005; Shafroth and others 2008), although these goals are not always achieved (Shafroth and others 2008). Saltcedar control efforts are now often coordinated at a river basin scale. For example, from 1999 to 2003 herbicide was applied to 4081 ha to kill saltcedar along 320 km of the Pecos River in Texas at a cost of $1.9 million (Hart and others 2005). Passage by the U.S. Congress of the 2006 *Saltcedar and Russian Olive Control Act* (Public Law 109-320) is part of the effort to coordinate saltcedar control efforts at the national scale.

### Potential for Erosion

Removing the dominant vegetation along thousands of kilometers of river, however, can have unintended consequences, including increased erosion (Millar 2000). Erosion can occur when boundary shear stress exceeds the critical shear stress to mobilize sediment particles in the channel boundary (Shields 1936). Boundary shear stress is reduced by factors that lower velocity near the bank, such as fluid drag on plant stems (Smith 2004, 2007). In addition, plant roots stabilize banks by reinforcing bank sediments (Simon and Collison 2002). Reducing erosion was a primary rationale for the original introduction of saltcedar in the western United States (Bryan and Post 1927). Removal of this and associated species could lead to substantial sediment erosion and transport, potentially increasing flood hazards for communities downstream and accelerating the filling of reservoirs with sediment (Barz and others 2009). Herbicide treatment of riparian vegetation along part of a river can set up a natural experiment to determine the importance of riparian vegetation for bank stability. In this article we document erosion and sediment transport during a flood that followed herbicide treatment of saltcedar along a data-rich river, the Rio Puerco, New Mexico (Fig. 1).

## Study Location

The Rio Puerco is an ephemeral stream draining 19,030 km$^2$ in north-central New Mexico (Fig. 1). Easily eroded, fine-grained sedimentary rocks dominate this semiarid watershed (Heath 1983; Love 1986), resulting in high sediment yields dominated by silt and clay (Nordin 1963; Clapp and others 2001). The stream channel banks and floodplain are composed mostly of sand with smaller amounts of silt and clay (Nordin 1963; Love 1986). Sand is more abundant in the channel banks and levees than in the distal parts of the floodplain (Friedman and others 2005b). Streamflow is largely unregulated, with only 15% of the watershed upstream from flood control structures. High flows typically result from convective thunderstorms between July and October and have durations ranging from hours to days (Heath 1983; Griffin and others 2005; Vivoni and others 2006).

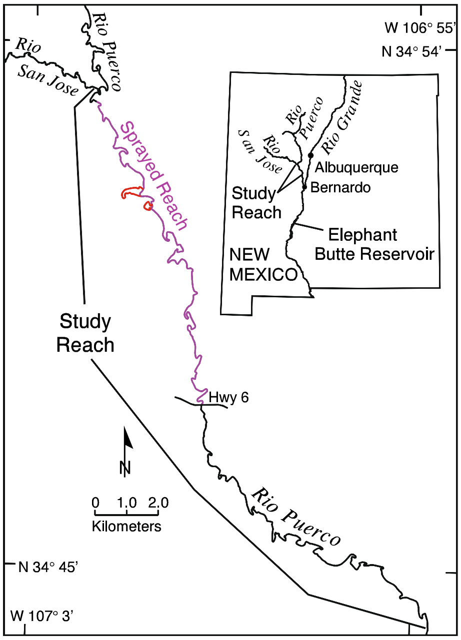

**Fig. 1** Location of the study reach along the Rio Puerco, New Mexico. The channel centerline after the flood of August 10, 2006 is shown in purple in the sprayed reach and in black in the unsprayed reaches upstream and downstream. The two meander bends cut off during the flood are shown in red. The river centerline was mapped from imagery acquired November 15, 2006

This watershed is the principal source of sediment to the Middle Rio Grande (Bryan 1928; Pierce 1962; Love 1986). Incision of the Rio Puerco from the mid 1800s through the early 1900s created an arroyo that was approximately 10 m deep, 100 m wide, and 200 km long (Bryan and Post 1927). Arroyo incision greatly decreased irrigated agriculture on the former floodplain of the Rio Puerco, and caused severe sedimentation downstream in the Rio Grande and in Elephant Butte Reservoir (Bryan 1928). In 1925, the Bureau of Reclamation, U.S. Department of the Interior, forecasted that this reservoir would fill with sediment by 1980 (Collins and Ferrari 2000), but that did not occur, in part because sediment output from the Rio Puerco declined greatly after about 1940 (Elliott and others 1999; Molnar and Ramirez 2001; Friedman and others 2005b). One reason for this dramatic decline in sediment output was the introduction, in 1926, of saltcedar along the Rio Puerco for erosion control (Bryan and Post 1927). Saltcedar is now the dominant riparian species in the lower 150 km of the Rio Puerco arroyo.

Because of their high density on the channel banks and floodplain, saltcedar and willow (*Salix* spp.) stems impose considerable drag on the flow (Smith and Griffin 2002). Furthermore, roots of these species reinforce the bank material and reduce the risk of mass failure (Simon and Collison 2002). The result should be decreased boundary shear stress and reduced bank erosion relative to conditions on a bank lacking woody vegetation (Kean and Smith 2004). Modeling efforts have begun to quantify the influence of vegetation on flow hydraulics along the Rio Puerco and elsewhere (Smith 2004; Kean and Smith 2004; Griffin and others 2005; Smith 2007). Herbicide application in 2003 to control saltcedar through a limited segment of the Rio Puerco arroyo and a subsequent flood in 2006 resulted in a natural experiment testing the importance of riparian vegetation to bank stability and erosion control. In this article, we take advantage of extensive channel geometry measurements made prior to the flood within and outside of the spray zone to investigate the erosional consequence of saltcedar control.

### Management Action

In September 2003, the Valencia Soil and Water Conservation District used a helicopter to spray the floodplain and channel banks of the Rio Puerco with the herbicide Imazapyr (trade name Arsenal). The sprayed reach extends upstream from the Highway 6 bridge for a distance of 11.7 km as measured along the valley axis to a point 0.5 km downstream from the confluence with the Rio San Jose (Fig. 1). Although the target of the herbicide treatment effort was saltcedar, the herbicide killed almost all the woody vegetation on the floodplain and channel banks, including sandbar willow (*Salix exigua* Nuttall), which had occurred as a dense fringe along much of the channel margin. Dead woody plant stems were left standing, and no restoration planting occurred. Over the next three years, streamflow removed the brittle dead stems along the channel banks.

### Flood of 2006

In the summer of 2006, thunderstorms caused several high flows in the Rio Puerco. The largest of these flows occurred on August 10 and had a peak discharge of 176 $m^3/s$ at Bernardo (U.S. Geological Survey streamflow-gaging station number 08353000), which is located 81 km downstream from Highway 6 (Fig. 1). The flood flow was more than a meter deep across the floodplain. The 2006 peak event was the highest flow measured at the Bernardo gage since 1972, but this discharge was exceeded in eleven of the 33 years between 1940 and 1972 (Friedman and others 2005b).

## Methods

We determined geomorphic changes resulting from the August 2006 flood along the Rio Puerco by comparing topographic data and imagery acquired before and after the flood. The data sources included high-precision topographic surveys, digital terrain models (DTMs) derived from airborne Light Detection and Ranging (LIDAR) survey data, and georeferenced digital imagery. We referenced all datasets to the UTM coordinate system, Zone 13N, NAD83, and we referenced elevations to NAVD 88. As a result of two meander cutoffs that occurred during the flood, distance along the channel did not provide a common distance reference before and after the flood. Therefore, we identified locations in terms of distance down-valley along the arroyo centerline from the confluence with the Rio San Jose.

In April 2002, prior to herbicide application and the flood, we surveyed cross sections and the longitudinal profile of the Rio Puerco channel in the first 14 km downstream from the Highway 6 bridge crossing (Fig. 1). We conducted the longitudinal survey using a high-precision, Real-Time Kinematic (RTK) global positioning system (GPS) with horizontal and vertical positional accuracy within 3 cm (*NAVSTAR GPS User Equipment Introduction* 1996; Satalich and Ricketson 1998; Trimble Navigation Limited 2004). We surveyed nine channel cross-sections using a tape, hand-level, and rod (Griffin and others 2005). We acquired DTMs developed from a dense set of LIDAR data processed to remove returns from vegetation and provide a bare ground surface model with 2-m point spacing (Spectrum Mapping, LLC, unpublished report 2005). The LIDAR data were collected in April and July 2005 for the Rio Puerco arroyo segment from Highway 6 (Fig. 1) downstream to Bernardo. Positional accuracy of the LIDAR data used to derive the DTMs is less than 0.30 m root mean square (RMS) error in all directions (Spectrum Mapping, LLC, unpublished report 2005). We verified positional accuracy of the identified bare ground surface under dense canopy using points obtained during the April 2002 RTK GPS survey at locations where elevation was unlikely to have changed. The average magnitude of the difference in elevation (i.e., average of the absolute value of the difference) for the 20 points was 0.13 m and the standard deviation of the difference was also 0.13 m.

Pre-flood imagery sources used to map edges of the channel and other geomorphic features (by eye) were October 1996 National Aerial Photography Program (NAPP) photographs and 2005 New Mexico Digital

Orthophoto Quarter-Quads (DOQQs; New Mexico Geospatial Data Acquisition Committee 2006). We scanned large-scale prints of the 1996 NAPP photographs and rectified them to produce georeferenced images with a resolution (pixel size) of 0.22 m. The ground sample distance in the source imagery for the DOQQs acquired in July and August 2005 is 1 m. While surveyed channel cross-sections provide precise point measurements of channel width and shape, high-resolution aerial photographs and satellite imagery provide continuous data for channel width as a function of distance down-valley. This is particularly important where width is highly variable, as was the case in the sprayed reach after the flood. Accuracy of the mapped location of the top of the bank is affected by pixel size in the source image as well as visibility of the edges of the channel, which is limited by canopy cover. Our previous application of this method along the Rio Puerco (Griffin and others 2005) found average channel width for an 81-km river segment was underestimated by about 2 m compared to average channel width determined from 35 surveyed channel cross-sections.

We determined post-flood geomorphic conditions from an RTK GPS topographic survey conducted in January 2007 and high-resolution satellite imagery acquired in November 2006. The January 2007 topographic survey included repeat surveys of channel and arroyo cross-sections in the first 14 km downstream from Highway 6. In addition, we surveyed 3 channel cross-sections upstream from the sprayed reach and 22 channel cross-sections within the sprayed reach. We measured downstream and down-valley gradients of the channel bed and floodplain, and we surveyed high-water marks from the August 2006 flood at 23 locations throughout the study reach.

Digital imagery acquired 15 November 2006 from DigitalGlobe Inc.'s QuickBird II satellite (panchromatic image with 60-cm pixel size) documented the post-flood channel and floodplain geomorphic conditions. DigitalGlobe Inc. georeferenced the image and made terrain corrections using a coarse (1-degree) digital elevation model. Absolute positional accuracy specified for the Quickbird II Standard Imagery Product (DigitalGlobe Inc. 2006) is 90% probability of less than 23-m circular error and RMS error less than 14 m. Horizontal offset errors in the image acquired 15 November 2006 are less than these values as a result of low terrain relief in the subject area (the Rio Puerco valley and arroyo) and a low off-nadir view angle (4.8°) during image acquisition. The image coverage polygon area (not rectangular) is 67.15 km$^2$, with a maximum extent of 15.91 km in the east-west direction and 29.28 km north-south. The maximum measured horizontal offset between coordinates in the November 2006 image and coordinates in the reference image (2005 DOQQs) for 29 identifiable points within the arroyo was 8.23 m, the mean offset was 6.79 m, and RMS error computed from these points was 6.84 m.

Errors in feature scale measured from the satellite image are small. For example, the difference in straight-line distance between the confluence with the Rio San Jose and the railroad bridge at the Highway 6 crossing measured from the November 2006 image (10,729 m) and 2005 DOQQs (10,732 m) was only 3 m (0.03%). Dimensions of channel-scale features that did not change between 2005 and 2006 (e.g., bridge widths) as compared to the same features measured from images acquired by other means (1996 NAPP photographs and the 2005 NM DOQQs) had errors of less than 1.2 m (2 times the pixel size).

We used the November 2006 image to map (by eye) post-flood edges of the channel and locations of sand deposits on the floodplain and to identify locations of large-scale geomorphic change (e.g., meander cutoffs) prior to the January 2007 field survey. We determined average channel widths for valley segments 0.5 km long, with the same spatial extent for each year, by dividing the area of the channel by the length of the channel centerline. This method minimizes the effects of local errors due to positional offset between images. Accuracy of the average channel width computed in this manner can be determined by comparing average widths computed from different source data in areas where channel width did not change during the flood.

We documented the extent of eroded banks throughout the study segment during the January 2007 field survey. We identified areas where recent bank erosion extended over half the height of the bank, drew their locations on image maps, and then digitized the maps. From these data we computed the fraction of total channel bank within 0.5-km valley segments that eroded during the August 2006 flood event.

We estimated volumes of sediment eroded from the channel banks within the sprayed reach by multiplying planimetric area of new channel created during the August 2006 flood event (determined from imagery) by the average depth of the eroded areas. This depth was estimated as the average height of the floodplain above the channel bed within the sprayed reach using the January 2007 survey data (3.6 m). We computed volumes of sediment deposited on the floodplain throughout the study segment by multiplying areas of deposition within 0.5 km arroyo intervals by the estimated deposit thickness. Deposits dominated by sand-sized sediment are clearly visible as white patches in the November 2006 image, and we mapped these patches as polygons. We confirmed whether or not a floodplain deposit was the result of the August 2006 flood event by comparing the November 2006 image to both the 1996 NAPP photograph and the 2005 NM DOQQ. Downstream from Highway 6, we measured deposit thickness using the

April 2002 GPS cross-section surveys, the April/July 2005 DTMs, four arroyo cross-sections surveyed in January 2007, and the pre- and post-flood floodplain longitudinal profiles. We did not measure floodplain sand deposit thickness upstream from Hwy 6 because of the absence of comparison pre-flood topographic data for this area.

## Results

### Bank Erosion

Within the sprayed reach of the Rio Puerco arroyo, erosion was extensive and highly variable during the 2006 flood. About 62% of the length of the banks (both left and right) were eroded (Fig. 2a), and erosion occurred in straight reaches as well as in meander bends, indicating that shear stresses through much of the sprayed reach were high enough to erode the banks and transport the eroded material downstream. Mean channel width increased by 84% (Table 1, Fig. 2c), and average post-flood channel cross-sectional area was 2.6 times larger in the sprayed reach than in the downstream unsprayed reach (Table 2, Fig. 2b). About 680,000 $m^3$ of sediment, predominantly sand, was eroded in the sprayed reach during the 2006 flood (Fig. 2d). In addition, two long meanders were cut off during the 2006 flood (Fig. 1), resulting in a 10% decrease in channel length between the Rio Puerco's confluence with the Rio San Jose and the Highway 6 bridge. The flood-related erosion within the sprayed reach appears to have been the most extensive channel-widening event along the Rio Puerco downstream of the Rio San Jose since the 1970s (Elliott and others 1999; Friedman and others 2005b). Although erosion of the channel banks was extensive, the two meander cutoffs were the only evidence of significant erosion on the floodplain revealed by our analysis of aerial photographs, repeat cross sections, and ground observations.

Upstream and downstream from the sprayed reach, in contrast, erosion was minor and similar to that observed during fieldwork in previous years. Erosion in the 2006 flood occurred only along 3.5% of the channel bank (Fig. 2a), mostly along the outside of sharp meander bends, where shear stress along the bank increased through the bend. Average channel width determined from imagery downstream from the sprayed reach did not change during the flood (Table 1, Fig. 2c). Repeat surveys downstream from the sprayed reach showed that channel cross-sectional area was 19% smaller in 2007 than in 2002 (Table 2, Fig. 2b) due to sediment deposition on point bars, and there were no meander cutoffs (Fig. 1). Bank and floodplain

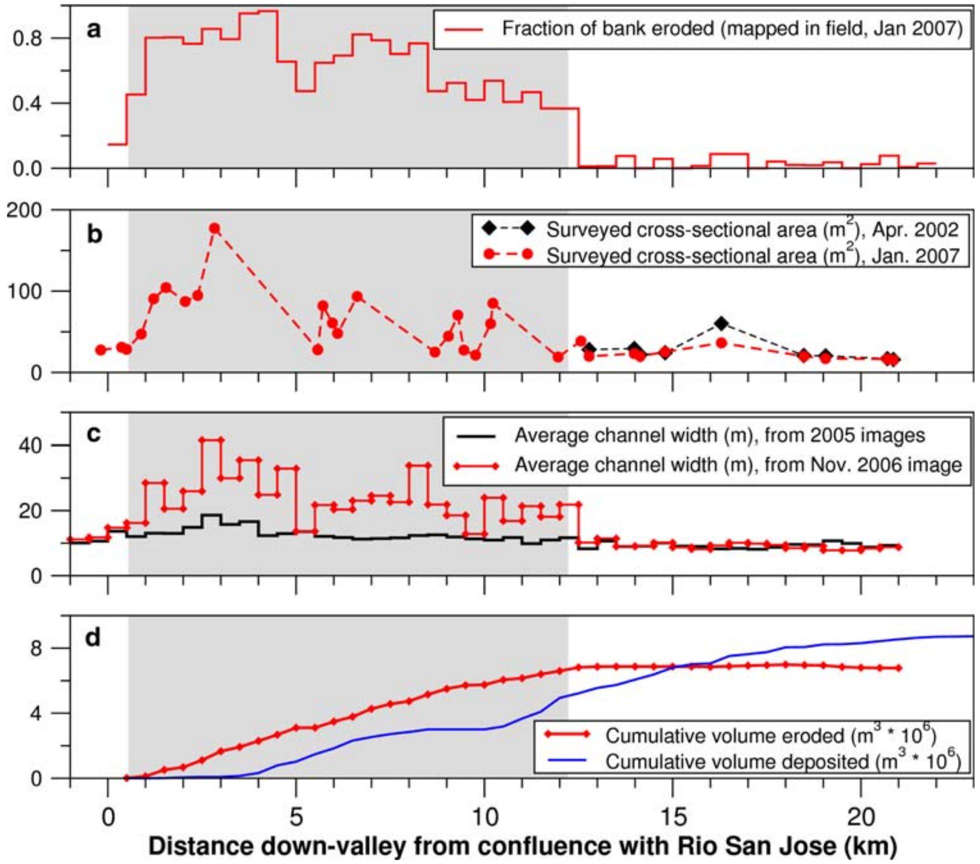

**Fig. 2** Longitudinal patterns of erosion of the Rio Puerco channel caused by the 2006 flood in the reach treated with herbicide (*shaded area*) and in untreated reaches upstream and downstream. **a** Fraction of the length of both banks where evidence of recent erosion was observed in the field after the flood. **b** Channel cross-sectional area after the flood in the entire study area, and before the flood in the untreated reach. **c** Comparison of pre- and post-flood channel width measured from imagery. **d** Cumulative volumes of sediment eroded from the channel banks and deposited on the floodplain

**Table 1** Mean channel width of the Rio Puerco, New Mexico, determined from imagery before the flood of August 10, 2006 (October 1996 and July/August 2005) and after the flood (November 2006), within the sprayed reach and downstream

| | Sprayed reach | | | Downstream from sprayed reach | | |
|---|---|---|---|---|---|---|
| | Mean | | | Mean | | |
| | Width (m) | S.D. | *n* | Width (m) | S.D. | *n* |
| October 1996 (pre-flood) | 13.5 | 2.45 | 25 | 11.6 | 1.86 | 17 |
| July/August 2005 (pre-flood) | 12.7 | 1.96 | 25 | 9.20 | 0.80 | 17 |
| November 2006 (post-flood) | 23.4 | 7.10 | 25 | 9.15 | 0.97 | 17 |

The sprayed and downstream reaches are 0.5–12.2 and 12.2–21.8 valley km downstream from the confluence with the Rio San Jose (Figs. 1 and 2)

*S.D.* standard deviation

**Table 2** Channel geometry parameters along the Rio Puerco, New Mexico, determined from field survey data before the flood of August 10, 2006 (April 2002) and after the flood (January 2007), within the sprayed reach and downstream

| | Sprayed reach | | | Downstream from sprayed reach | | |
|---|---|---|---|---|---|---|
| | Mean | S.D. | *n* | Mean | S.D. | *n* |
| April 2002 (pre-flood) | | | | | | |
| Width (m) | – | – | – | 18.3 | 10.1 | 9 |
| Depth (m) | – | – | – | 1.50 | 0.27 | 9 |
| Area ($m^2$) | – | – | – | 26.4 | 13.5 | 9 |
| January 2007 (post-flood) | | | | | | |
| Width (m) | 26.0 | 15.7 | 22 | 14.0 | 5.90 | 9 |
| Depth (m) | 2.30 | 0.42 | 22 | 1.58 | 0.19 | 9 |
| Area ($m^2$) | 61.5 | 38.3 | 22 | 21.5 | 6.43 | 9 |

The sprayed and downstream reaches are 0.5–12.2 and 12.2–21.8 valley km downstream of the confluence with the Rio San Jose (Figs. 1 and 2)

Width is mean top width, depth is mean depth, area is mean cross-sectional area, and S.D. is standard deviation. No data are available for the sprayed reach in 2002

vegetation remained dense in January 2007 and showed little sign of flood damage.

## Floodplain Deposition

Sand eroded from the sprayed reach was carried an average of 5 km down valley (Fig. 2d) and deposited on the floodplain and channel bed (Fig. 3). Sand splays on the floodplain were clearly visible in the high-resolution satellite image, both within the sprayed reach and up to 10 km down-valley. Because of their lower settling velocities, mechanically dispersed silt and clay in suspension probably traveled farther downstream, or were deposited from ponded water in floodplain depressions disconnected from the down-valley flow. At Highway 6, just downstream from the sprayed reach, the floodplain and channel aggraded by about 1.3 m (Fig. 3), although channel dimensions changed little (Table 2). This was the greatest sediment deposition event in this location since 1972 (Friedman and others 2005b). Five km down-valley from Highway 6, the average depth of sediment deposited on the floodplain and channel bed was less than 50 cm.

Average deposit thickness at 15 locations downstream from Highway 6 decreased as a function of distance down-valley. An exponential regression fit to the 15 points is:

$$H_{\mathrm{dep}} = 10.579 * \exp(-0.17862 * Valkm),$$

where $H_{\mathrm{dep}}$ is the average deposit thickness (m) and *Valkm* is the distance down-valley from the Rio San Jose (km). The standard error of the estimated thickness compared to the 15 known values is 0.21 m, the average error is 0.04 m and $r^2$ for the regression is 0.72. The furthest upstream deposit of sand on the floodplain occurred 0.5 km down-valley from the upstream end of the sprayed reach (valley km 1.0). The thickness of sand deposits on the floodplain within the sprayed reach is unknown due to the lack of pre-flood topographic data within that reach. For the purpose of estimating the volume of deposited sediment within the sprayed reach, we assumed that average deposit thickness increased linearly from 0 at this point to 1.1 m at Highway 6 (from valley km 1.0 to valley km 12.2).

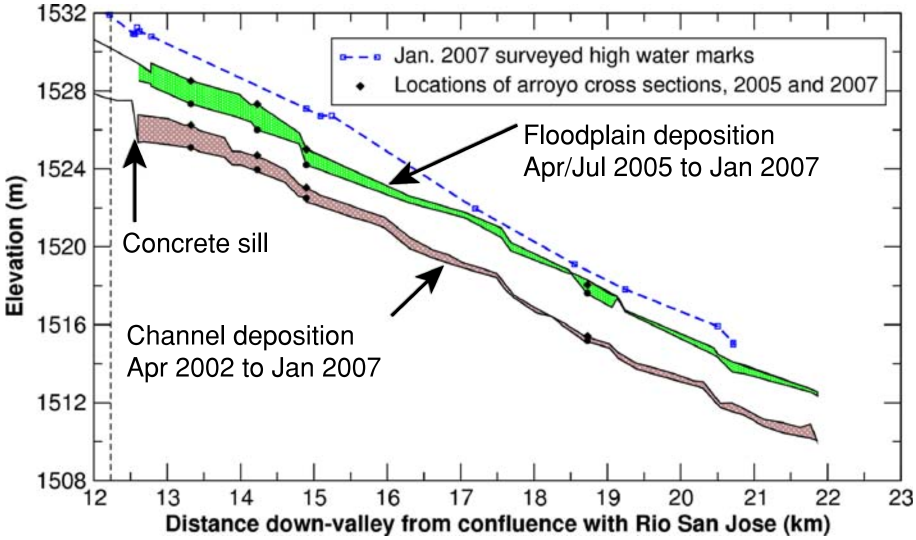

**Fig. 3** Sediment deposition (*colored polygons*) on the floodplain and channel bed in the first 10 km down-valley from the sprayed reach, inferred from pre- and post-flood topographic data. The vertical dashed line at 12.2 km marks the location of the Highway 6 bridge at the downstream limit of the sprayed reach

## Discussion

During the flood of 2006, extensive erosion occurred in the sprayed reach, but not upstream or downstream of this area. The predominant form of erosion in the sprayed reach was lateral retreat of the channel banks. Vertical incision of the bed and floodplain were minor. Our data indicate that herbicide application, by effectively killing bank-stabilizing vegetation, increased susceptibility of the banks to lateral erosion.

Specifically, the pattern of erosion along the Rio Puerco suggests that the principal cause was elimination of woody bank vegetation that had produced drag on the flow, resulting in an increase in boundary shear stress along the bank within the sprayed reach. Modeling studies of the Rio Puerco channel have shown that removing the saltcedar and willow stems from the bank greatly increases the boundary shear stress at the toe of the bank (Kean and Smith 2004; Griffin and others 2005; Smith 2007). The increased boundary shear stress led to particle erosion at the toe, failure of the over-steepened bank, transport of sediment downstream, and widening within the sprayed reach. A contributing mechanism was likely reduced root tensile strength and resistance to bank failure caused by the herbicide application (Schmidt and others 2001; Simon and Collison 2002; Pollen-Bankhead and others 2009). Associated meander cutoffs (Fig. 1) increased local gradient, raising boundary shear stress and further contributing to widening.

We considered other possible causes of large-scale bank erosion within the sprayed reach. Longitudinal profiles and mapped arroyo features show that average width of the arroyo as well as floodplain and channel gradients within the sprayed reach are similar to those upstream and downstream. There are no significant bedrock controls on channel flow in the study area. A concrete wall and steps protecting a railroad bridge near the Highway 6 crossing do provide a control on bed elevation upstream from Highway 6. However, surveyed high-water marks indicate the flood water-surface slope did not change in the vicinity of the highway and railroad bridges (Fig. 3). Surveyed high-water marks and channel cross-sections indicate the flood peak discharge in the sprayed reach was similar to discharge immediately upstream and downstream. The upstream limit of the eroded and sprayed zone is 0.5 km downstream of the confluence with the Rio San Jose (Fig. 1). It is possible that discharge below this confluence was significantly higher than discharge on either tributary upstream, which could explain erosion beginning downstream of the confluence, but this would not explain the absence of bank erosion in the 0.5-km section of river valley between the confluence and the upstream limit of herbicide application (Fig. 2). The only sources of inflow between the confluence with the Rio San Jose and Highway 6 are small gullies, which would have contributed limited local runoff insufficient to raise the flood peak discharge substantially within the sprayed reach. Therefore, the effects of herbicide application on the bank vegetation provide the only reasonable explanation for the spatial pattern of erosion along the Rio Puerco during the 2006 flood.

Because our pre-flood topographic survey was in 2002, four years prior to the flood, there is a possibility that some of the channel change downstream from Highway 6 that we have attributed to the flood actually occurred earlier, between 2002 and 2006. The increase in bed elevation downstream from Highway 6 between April 2002 and January 2007 (Fig. 3) likely included some deposition from in-channel flows and a near-bankfull flow that occurred on 14 September 2003 (Vivoni and others 2006). However, comparison of the DTMs derived from the April/July 2005

LIDAR survey and data from the April 2002 GPS survey indicated there was little deposition on the channel levees or floodplain during the intervening period. During a field inspection in June 2005, we observed no evidence of recent bank erosion in the sprayed reach or downstream. For these reasons, we are confident that the bulk of the observed erosion and deposition occurred during the 2006 flood.

## Management Implications

The magnitude of the erosional response to phreatophyte control will depend upon the treatment strategy as well as site conditions. Erosion along the Rio Puerco in 2006 occurred as lateral retreat of stream banks. Erosion would have been reduced, therefore, if the bank vegetation, mostly sandbar willow and saltcedar, had not been killed (Millar 2000; Simon and Collison 2002; Griffin and others 2005). In contrast, if the standing dead plant stems on the floodplain had been removed mechanically or by fire, the decreased fluid drag could have resulted in higher velocities and increased erosion on the floodplain (Smith 1976; Smith 2004). Moreover, successful planting of desired vegetation along the bank following herbicide treatment would minimize the time during which the bank is susceptible to erosion (Shafroth and others 2005, 2008). Where control of riparian vegetation is planned over a long river reach, carrying out the control in stages over many years would avoid leaving a long section of bank susceptible to erosion.

Our results show that banks vegetated by saltcedar and sandbar willow are more stable than unvegetated banks. The relative increase in bank stability resulting from the presence of saltcedar relative to other riparian species, however, is still unclear (Trimble 2004). In the early to mid-1900s, introduction of saltcedar was followed by channel narrowing along many western rivers including the Rio Puerco (Friedman and others 2005b). Some authors have argued that saltcedar caused the narrowing (Graf 1978; Birken and Cooper 2006). Others have argued that saltcedar is no more effective than native species at promoting channel narrowing, and that the 20th century narrowing was caused by declines in peak flows related to water management and climate (Everitt 1998). In the present study, flood-related channel widening occurred after killing by herbicide of both the introduced saltcedar and the native sandbar willow. Therefore, we are unable to draw inferences about the relative effectiveness of these or other species in bank stabilization. Addressing this issue will require controlled comparisons along river banks or flumes, or modeling studies that incorporate the effects of the density, flexibility and strength of stems (Griffin and others 2005; Smith 2007) as well as the density and tensile strength of roots (de Baets and others 2007; Pollen-Bankhead and others 2009).

Not all rivers are as susceptible as the Rio Puerco to erosion following phreatophyte control. Susceptibility to erosion is decreased by any factor that decreases shear stress on the bank or increases critical shear stress. For example, construction of large dams along rivers typically allows storage of floods, reducing the frequency and magnitude of peak discharges and shear stress downstream (Graf 2006). The more heavily regulated the flow, the less likely floods would be large enough to cause the erosional response observed here. In addition, the critical shear stress for erosion is low for sand-sized particles. Larger particles such as gravels and cobbles are more difficult to dislodge because of their greater mass, while smaller particles such as silt and clay are more difficult to dislodge because of cohesive forces (Thorne and Tovey 1981; Papanicolaou and others 2007). The Rio Puerco is vulnerable to erosion because flow is flashy and mostly unregulated, and because the sandy banks have low critical shear stress for erosion. Rivers less prone to flooding or with more resistant bank materials should have less risk of erosion following vegetation removal.

Erosion and sediment transport are natural processes. Because of a high variability in flow and relatively sparse riparian vegetation, stream ecosystems in the arid and semi-arid western United States often carry high sediment loads and can fluctuate greatly in channel width and location (Wolman and Gerson 1978). Many native riverine species require such physical disturbance for long-term persistence (Friedman and Lee 2002). Where invasive riparian vegetation has narrowed and stabilized the channel, removal of this vegetation may be desirable to promote a more dynamic channel and the native species a dynamic channel supports (Pollen-Bankhead and others 2009), but this may conflict with uses of the river that require a stable channel or lower sediment loads (Auble and others 1997; Barz and others 2009). Flood-related erosion of the Rio Puerco Arroyo in the early 1900s forced abandonment of agricultural communities (Bryan 1928) and damaged the Pottery Mound, a major archaeological site in the valley (Emslie 1981). Extensive chemical or biological control of saltcedar along the Rio Puerco without revegetation could renew the erosion that damaged these areas in the past. Downstream from the confluence of the Rio Puerco and Rio Grande are Elephant Butte Reservoir and most of the remaining habitat of the endangered Rio Grande silvery minnow (*Hybognathus amarus*) (Ikenson 2002). These resources could be damaged by greatly increasing sediment discharge from the Rio Puerco into the Rio Grande. In fact, saltcedar was intentionally introduced to the Rio Puerco in 1926 to reduce damage caused by sedimentation in the Rio

Grande and in Elephant Butte Reservoir (Bryan and Post 1927; Pierce 1962).

The importance of vegetation for bank stability is well known (Smith 1976; Hickin 1984; Simon and Collison 2002; Kean and Smith 2004). Measurements of the erosional consequences of vegetation removal at the river-reach scale, however, are scarce (Pollen-Bankhead and others 2009). Studies such as ours aid understanding of the mechanism of bank stabilization by vegetation and help to quantify the potential erosion that can result from future phreatophyte removal projects.

We have demonstrated that removal of invasive riparian vegetation can lead to extensive erosion in a subsequent flood. Pollen-Bankhead and others (2009) observed a smaller increase in the rate of bank retreat during moderate flows following removal of saltcedar and Russian olive in Canyon de Chelly, Arizona. The debate over where and how to control nonnative riparian vegetation is complex (Zavaleta 2000; Shafroth and others 2005; Stromberg and others 2007). In this mix, however, consideration must be given to the potential for accelerated erosion and downstream sedimentation resulting from control of saltcedar or any other riparian plant. Models are needed to enable managers to make quantitative assessments of the potential for erosion at different sites. To be effective, these models must accurately depict both (1) the effect of plant stems on the boundary shear stress at the toe of the bank as well as (2) the effect of plant roots on the resistance of the bank to mass failure.

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