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The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region

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ABSTRACT

Over the last century, large-scale water development of the upper Rio Grande in the U.S. and Mexico, and of the Rio Conchos in Mexico, has resulted in progressive channel narrowing of the lower Rio Grande in the Big Bend region. We used methods operating at multiple spatial and temporal scales to analyze the rate, magnitude, and processes responsible for channel narrowing. These methods included: hydrologic analysis of historic stream gage data, analysis of notes of measured discharges, historic oblique and aerial photograph analysis, and stratigraphic and dendrogeomorphic analysis of inset floodplain deposits. Our analyses indicate that frequent large floods between 1900 and the mid-1940s acted as a negative feedback mechanism and maintained a wide, sandy, multi-threaded river. Declines in mean and peak flow in the mid-1940s resulted in progressive channel narrowing. Channel narrowing has been temporarily interrupted by occasional large floods that widened the channel, however, channel narrowing has always resumed. After large floods in 1990 and 1991, the active channel width of the lower Rio Grande has narrowed by 36–52%. Narrowing has occurred by the vertical accretion of fine-grained deposits on top of sand and gravel bars, inset within natural levees. Channel narrowing by vertical accretion occurred simultaneously with a rapid invasion of non-native riparian vegetation (*Tamarix* spp., *Arundo donax*) which created a positive feedback and exacerbated the processes of channel narrowing and vertical accretion. In two floodplain trenches, we measured 2.75 and 3.5 m of vertical accretion between 1993 and 2008. In some localities, nearly 90% of bare, active channel bars were converted to vegetated floodplain during the same period. Upward shifts of stage-discharge relations occurred resulting in over-bank flooding at lower discharges, and continued vertical accretion despite a progressive reduction in stream flow. Thus, although the magnitude of the average annual flood was reduced between 40 and 50%, over-bank flooding continued. These changes reflect a shift in the geomorphic nature of the Rio Grande from a wide, laterally unstable, multi-thread river, to a laterally stable, single-thread channel with cohesive, vertical banks, and few active in-channel bars.

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1. Introduction

The morphology of river channels adjusts in response to changes in flow regime and the amount and size of the supplied sediment (Lane, 1955). Dams, reservoirs, and diversions disrupt the flow regime and sediment supply (Petts 1984; Williams and Wolman, 1984; Meade et al., 1990; Schmidt and Wilcock, 2008), and these disruptions may create an imbalance between sediment influx and efflux in reaches downstream. If the imbalance is sufficiently large, sediment evacuation or accumulation, dependent on the relative magnitude of changes in flow and sediment supply, may ensue (Schmidt and Wilcock, 2008). Sediment accumulation occurs where the reduction in sediment transport capacity is greater than the reduction in sediment supply, or where sediment supply increases. Channel and floodplain aggradation and/or channel narrowing result (Everitt, 1993; Friedman et al., 1996, 1998, Allred and Schmidt, 1999), and the style and magnitude of the channel adjustments vary in relation to the width of the alluvial valley, properties of the bed and bank material, and characteristics of the riparian vegetation.

Channel change may occur slowly (Mackin, 1948; Schumm and Lichty, 1965) or rapidly (Everitt, 1993; Zahar et al., 2008), and the rate at which channel change occurs partly depends on whether negative or positive feedback mechanisms prevail. In the case where channel change is driven by sediment accumulation, the long-term rate of bed or floodplain aggradation may be moderated by internal negative feedbacks such as an increase in slope and/or bed fining, or temporarily reversed by external processes such as large floods and base level changes (Chorley and Kennedy, 1971; Schumm, 1973; Erskine and Warner, 1988).

Conversely, the rate of sediment accumulation may be exacerbated by positive feedback mechanisms (Zahar et al., 2008). One positive

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feedback occurs on fine grained rivers when riparian vegetation invades parts of the channel during drought (Schumm and Lichty, 1963; Burkham, 1972; Pollen-Bankhead et al, 2009). Vegetation is effective at stabilizing channel banks and bars (Thorne, 1990; Abernethy and Rutherford, 2001; Gran and Paola, 2001; Simon and Collison 2002; Griffin and Smith, 2004), reducing channel-margin flow velocities and shear stresses (Kouwen et al., 1969; Carollo et al., 2002, Kean and Smith, 2004; Tal et al., 2004; Griffin et al., 2005; Tal and Paola 2007), and inducing sedimentation (Tooth and Nanson, 2000; Schultz et al., 2003). Thus, vegetation can exacerbate processes of channel narrowing during low flow periods by promoting sediment deposition within the channel and on the floodplain. The invasion of riparian vegetation, predominantly by non-native tamarisk (*Tamarix* spp.), has been extensive in the western U.S. and has contributed to the widespread narrowing of channels (Graf, 1978; Hereford, 1984; Everitt, 1993; Allred and Schmidt, 1999; Grams and Schmidt, 2002; Friedman et al., 2005; Birken and Cooper, 2006).

Although the existence of geomorphic feedbacks is well known (Chorley and Kennedy, 1971; Schumm, 1973), no case studies have explicitly demonstrated how negative and positive feedbacks affect the style of geomorphic change on one river system. The lower Rio Grande in the Big Bend region of Texas, Chihuahua, and Coahuila is one place where temporal and spatial data are of sufficiently long duration, precision, and complementarity to establish such a linkage. In this paper, we describe the characteristics of negative and positive feedbacks that have existed at different times during the past century. We demonstrate that large floods at the beginning of the 20th century acted as negative feedbacks by maintaining the historically wide, sandy channel. A decline in the frequency of large floods in the mid-1940s, however, resulted in the development and persistence of positive feedback mechanisms when accelerated declines in stream flow and increases in non-native riparian vegetation caused channel narrowing. The persistence of positive feedbacks since the 1940s has resulted in a progressive decline in channel width even though large floods still occasionally occurred.

Although the transformation of the channel and floodplain of the Rio Grande in the Big Bend region is widely recognized, it has never been quantified. We quantify the rate and magnitude of channel narrowing and vertical floodplain accretion and show that positive feedback mechanisms have led to unusually high rates of sediment accumulation. Efforts of rehabilitation are currently planned, and the history of channel change described here provides an essential perspective in planning effective rehabilitation programs.

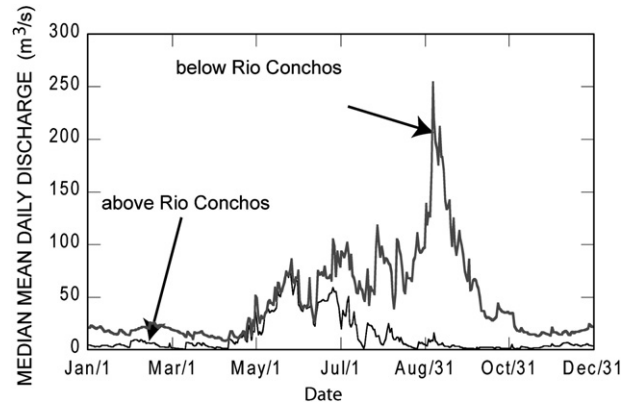

Fig. 2. Hydrographs of median mean daily discharge prior to 1915 at flow gages on the Rio Grande, above and below the Rio Conchos. See Fig. 1b for location of gages.

2. Study area

The Big Bend region extends from the confluence of the Rio Grande and Rio Conchos 490 km downstream to Amistad Reservoir (Fig. 1). Stream flow from the Rio Conchos significantly changes the flow regime of the Rio Grande; thus, we refer to the Rio Grande upstream from the Rio Conchos as the upper Rio Grande and downstream from the Rio Conchos as the lower Rio Grande.

Today, the Rio Grande in the Big Bend region is single-threaded and flows through wide alluvial valleys in structural basins and narrow canyons cut through intervening ranges. Some of the canyons are very narrow and the channel is entirely confined by bedrock. In wider canyons, alluvium forms some or all of the channel banks. Average channel slope is approximately 0.0013 in the alluvial valleys and 0.002 in the canyons. The bed of the Rio Grande is predominately sand and mud, although gravel bars occur at the mouths and downstream from ephemeral tributaries.

Rio Grande floods transport large suspended loads. Sources of fine sediment are the Rio Conchos downstream from Luis Leon Dam (Fig. 1) and ephemeral tributaries that drain the Chihuahuan Desert. Floods on these tributaries sometimes are very large and exceed the magnitude of the long-term average annual flood of the lower Rio Grande, yet the combined flow of all of the ephemeral tributaries is a small fraction of the total flow of the Rio Grande.

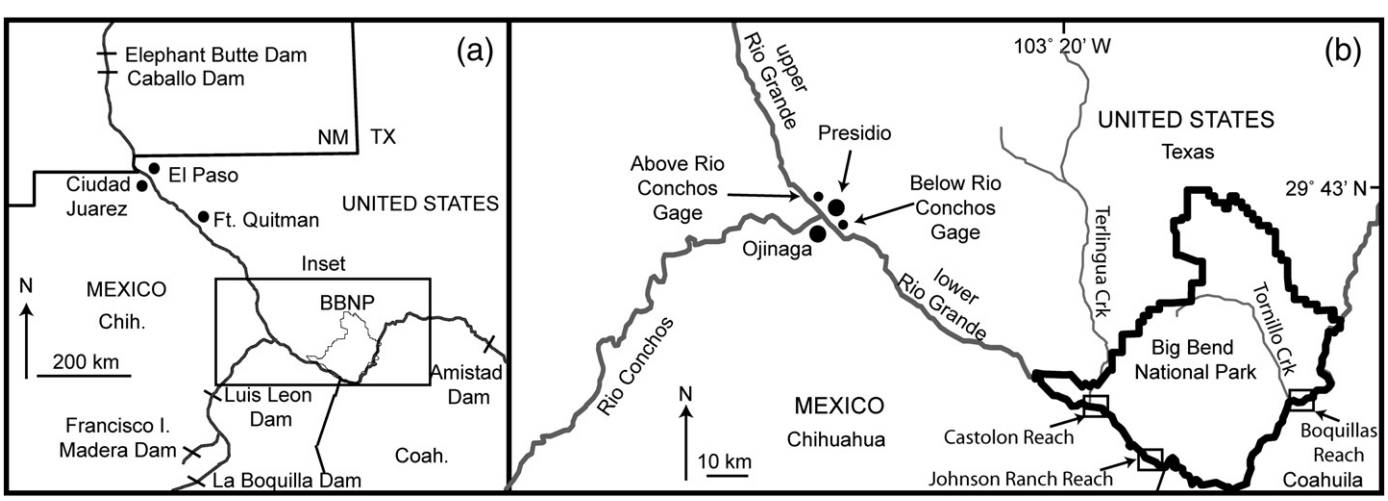

Fig. 1. (a) Map of the Big Bend region. (b) Study area.

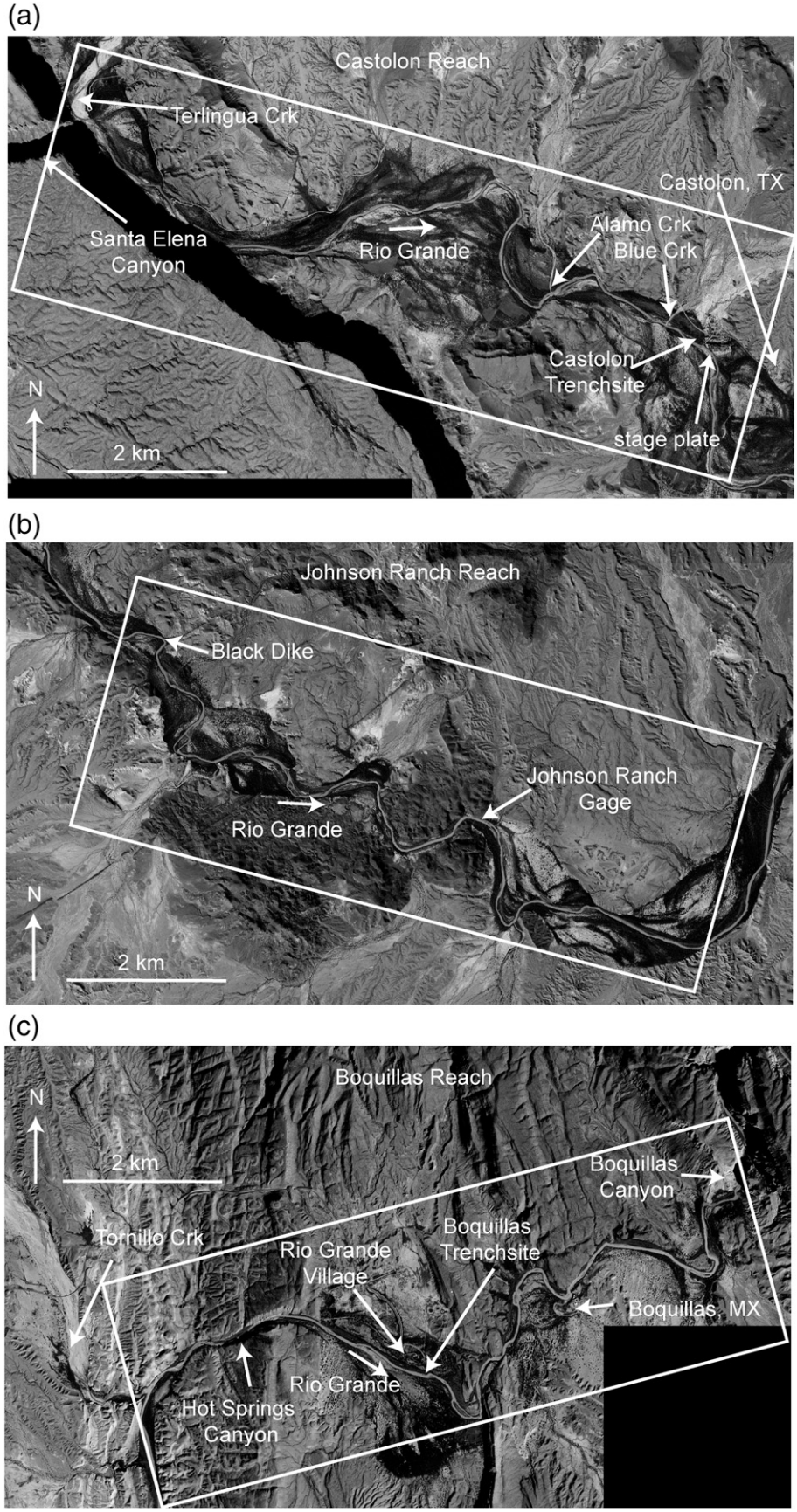

Fig. 3. (a) Castolon reach, (b) Johnson Ranch reach, (c) Boquillas reach.

3. Hydrologic and geomorphic background

Stream flow of the lower Rio Grande in the early 20th century primarily came from the Rio Conchos even though the basin area of the upper Rio Grande is more than twice its size. More than 66% of the total stream flow came from the Rio Conchos between August and February (Schmidt et al., 2003). The only months when the stream flow of the lower Rio Grande was dominated by inflow from the upper Rio Grande was between April and June during snowmelt in the southern Rocky Mountains (Fig. 2).

Stream flow was profoundly changed by La Boquilla Dam, completed in 1915 on the Rio Conchos, and by Elephant Butte Dam in southern New Mexico, completed in 1916 (Stevens, 1938; Everitt, 1998, Schmidt et al., 2003). Stream flow was further impacted by Francesco I. Madera (completed in 1947) and Luis L. Leon Dams (1967) in the Rio Conchos basin and Caballo Dam (1938), immediately downstream from Elephant Butte Dam (Stevens, 1938; Schmidt et al., 2003). Operations of Elephant Butte and Caballo Dams, and irrigation diversions in the El Paso–Juarez valley completely eliminated the natural spring snowmelt flood of the upper Rio Grande (Schmidt et al., 2003). Virtually no flow now passes beyond Fort Quitman, TX (Everitt, 1998). Today, more than 90% of the present stream flow of the lower Rio Grande comes from the Rio Conchos, even though stream flow from the Rio Conchos has also declined greatly (Schmidt et al., 2003).

In the early 20th century, the Rio Grande was wide, meandering, multi-threaded, and prone to avulsion (Mueller, 1975; Stotz, 2000). Riparian vegetation communities were heterogeneous with sparse, flood tolerant patches of seep-willow (*Baccharis glutinosa*) on sand bars, discontinuous stands of willow (*Salix exigua*) and cottonwood (*Populus* spp.) at the channel margins, and dense thickets of mesquite (*Prosopis* spp.) set back from the channel margins (Ainsworth and Brown, 1933; Everitt, 1998; Stotz, 2000).

Everitt (1993) shows that the nearly complete depletion of stream flow and the continued delivery of sediment from ephemeral tributaries that enter the upper Rio Grande between Ft. Quitman and Presidio caused the channel to narrow by approximately 90% between 1902 and 1970. The bed aggraded more than 2 m, and vertical accretion of the floodplain occurred. Reduced transport capacity of the river resulted in accumulation of coarse debris at tributary mouths that locally steepened the river profile. Everitt (1993, 1998) classifies these geomorphic changes into three evolutionary stages: (1) a period of channel shrinking when reductions in discharge led to in-channel aggradation and increases in river stage, (2) a period when over-bank flooding resumed because of the reduced channel capacity which led to valley-wide aggradation, and (3) a period of gravel accumulation at tributary mouths that altered the longitudinal profile into a series of steps. These results are important because they are the only documentation of channel change on the Rio Grande along this portion of the U.S./Mexico border.

The establishment of non-native vegetation, dominated by tamarisk and giant cane (*Arundo donax*), coincided with channel narrowing. Tamarisk was present in west Texas by 1912, and giant cane was present in the Presidio Valley in 1938 (Ainsworth and Brown, 1933; LeSeur, 1945; Everitt, 1998). Tamarisk and giant cane are now two of the dominant riparian species along much of the Rio Grande (Moring, 2002). Although Everitt (1980, 1998) recognizes that the establishment of vegetation may exacerbate the processes of channel narrowing and floodplain accretion, Everitt (1993, 1998) argues that changes in river form resulted from flow depletion alone.

Here, we show that geomorphic changes of the lower Rio Grande are similar to those described by Everitt (1993) further upstream, despite completely different hydrologic alterations. We also show that non-native vegetation has acted as a positive feedback mechanism by exacerbating processes of channel narrowing and vertical floodplain accretion, especially during the most recent period of low stream flows.

4. Methods

All field work was conducted within Big Bend National Park (BBNP) and in adjacent parts of Chihuahua and Coahuila. We analyzed channel change in three study reaches: (1) 14.5 km between the mouth of Terlingua Creek and Castolon, TX, referred to as the Castolon reach, (2) 12.5 km in the vicinity of the Johnson Ranch gage, referred to as the Johnson Ranch reach, and (3) 12.1 km near Boquillas, Coah., referred to as the Boquillas reach (Fig. 3). A stage plate near Castolon has been read daily since 1984, and is located approximately 100 m downstream from a trench that we excavated to analyze floodplain stratigraphy (Fig. 3). The Johnson Ranch reach includes the Johnson Ranch stream gage operated by the International Boundary and Water Commission (IBWC) (gage number 08375500). To analyze stratigraphy in the Boquillas reach, we excavated a trench in the floodplain approximately 2 km upstream from Boquillas, Coah. (Fig. 3).

We utilized methods that described channel change at multiple temporal and spatial scales, thereby allowing us to develop a history of channel change that is temporally precise and spatially robust. Temporally detailed data include changes in rating relations near Castolon, channel measurements derived from discharge measurement notes near Johnson Ranch, and stratigraphic and dendrogeomorphic characteristics of the modern floodplain interpreted in the trenches. Spatially extensive data included 27 repeated ground-level photographs originally taken in the early to mid 20th century and analysis of aerial photographs first taken in 1941.

4.1. Hydrologic analysis

We analyzed mean daily discharge data collected at the Johnson Ranch gage and compared those data with the longer-term record of the gage 8 km downstream from the Rio Conchos near Presidio (gage number 08374200, hereafter referred to as below Rio Conchos, BRC). Gaging began at BRC in May 1900, but was discontinued between April 1914 and January 1931. Gaging began at Johnson Ranch in 1936. We

Table 1
Flight dates for aerial photographs.

Castolon Reach			Johnson Ranch Reach			Boquillas Reach		
Flight date	Discharge (m^3/s)	Scale	Flight Date	Discharge (m^3/s)	Scale	Flight date	Discharge (m^3/s)	Scale
7/12/1941	44.2	1:24,000	7/17/1941	39.4	1:24,000			
10/26/1948	34	1:48,000	10/26/1948	34	1:48,000			
						Late 1950s	Unknown	1:56,000
10/17/1968	47.3	1:36,000	10/17/1968	47.3	1:36,000			
5/5/1986	16	1:24:000	11/4/1984	16.9	1:24:000	10/18/84	39.4	1:24:000
2/22/1991	28.2	1:31680	4/2/1991	29.2	1:31680	3/5/91	32.6	1:15840
2/6/1996	8.62	1:31680	2/6/1996	8.62	1:31680	2/15/96	8.1	1:31680
11/4/2004	9.22	DOQQ, 1m[a]	11/4/2004	9.22	DOQQ, 1 m*	11/4/04	9.22	DOQQ, 1m[a]

[a] = 1 m resolution, DOQQ = digitally ortho-rectified quarter quadrangle.

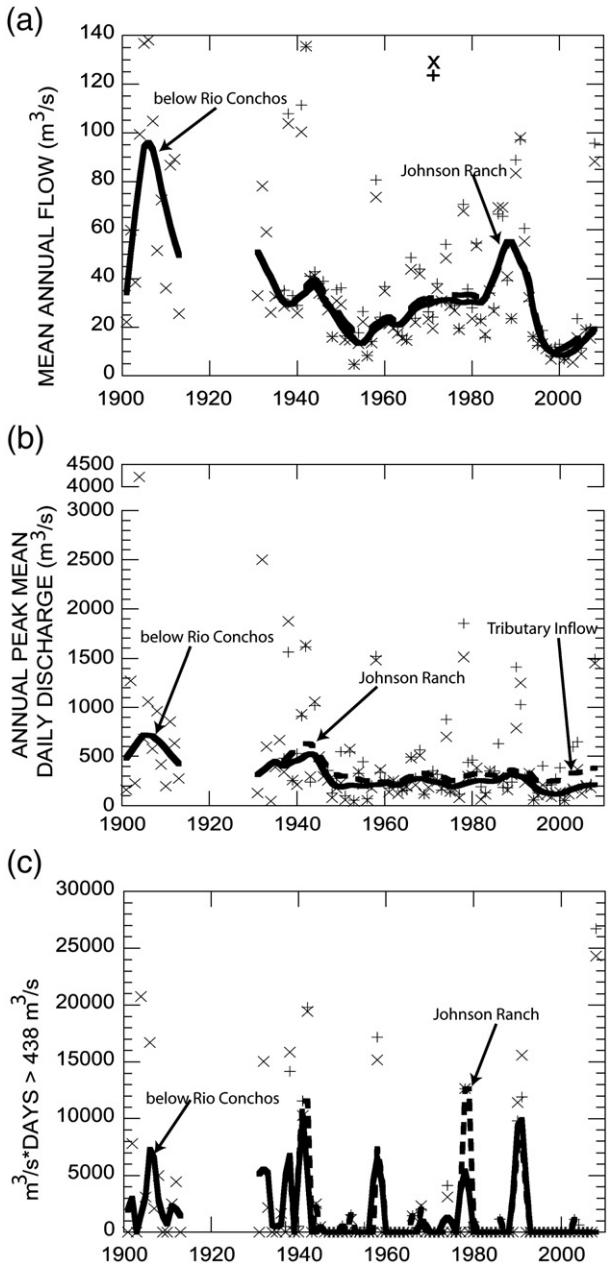

Fig. 4. (a) Characteristics of mean annual flows for the Rio Grande at the BRC and Johnson Ranch gages. (b) Characteristics of peak flows for the Rio Grande at the BRC and Johnson Ranch gages. A 10-year running average is shown in solid and dashed lines for both (a) and (b). (c) Statistics of flow duration for BRC and Johnson Ranch gages. Duration is in m^3/s days greater than the long-term average annual flood at Johnson Ranch of 438 m^3/s. A 5-year running average is shown in solid and dashed lines.

calculated annual and long-term average statistics for each gage based on the calendar year.

4.2. Analysis of repeated historic oblique photographs

We reoccupied historic photograph locations and replicated these photos at 18 locations within the three study reaches and nine locations elsewhere in BBNP. We compared changes between the historic and repeated photographs by describing changes in channel width, accumulation or evacuation of sediment, and changes in vegetation cover and type. We estimated the width of the channel in 1901, prior to aerial photography in the 1940s, by analyzing channel width depicted in two oblique photographs taken in Hot Springs Canyon (Fig. 3). In a GIS, we calculated the average channel width within the field of view of the two historic photos, and compared channel conditions to those depicted on digitally ortho-rectified quarter quadrangles (DOQQs) taken in 2004. We used the same technique to evaluate channel change in an alluvial reach immediately downstream from Hot Springs Canyon using a repeated photo originally taken in 1945. The latter photo match helped us extend the record of channel change at least a decade prior to the oldest aerial photographs of the Boquillas study reach.

4.3. Analysis of discharge measurements notes

We analyzed discharge measurement notes and stage measurements for the Johnson Ranch gage and the Castolon stage plate. Although discharge measurements have been collected near Johnson Ranch since 1936, we were only able to obtain measurement notes from 1970 and between 1979 and 2006. Each discharge measurement includes water depth and mean velocity at a minimum of 20 points across the channel. Because stage at the time of measurement is recorded in relation to a fixed reference mark, channel cross-section elevation can be compared throughout the period of available data (Smelser and Schmidt, 1998). Near Castolon, National Park Service (NPS) rangers collect stage measurements every morning.

We created stage-discharge rating relations for Johnson Ranch and Castolon, because they are not available from the IBWC or the NPS. We identified the timing and magnitude of shifts in the relations. We created rating relations at the Castolon stage plate based on discharge measured at Johnson Ranch, and the estimated time of travel. Measurements of channel area, channel width, and mean velocity were plotted against discharge to construct at-a-station hydraulic geometry relations. A wide scatter occurs among these data; thus, we used the 95% confidence interval bands about the mean relations to analyze changes. We investigated changes in cross-section shape at the Johnson Ranch gage by comparing cross-section measurements collected at flows that were approximately the magnitude of the 2-yr flood.

4.4. Stratigraphic and dendrogeomorphic analysis of inset floodplain deposits

We excavated two trenches through the floodplain and mapped and interpreted the exposed alluvial stratigraphy. We excavated tamarisk and willow rootstock, determined the date and elevation of germination (Hereford, 1984), and analyzed changes in tree ring anatomy due to burial (Friedman et al., 2005). We compared the elevations of the burial signals to the location of stratigraphic contacts to identify years in which individual stratigraphic units were deposited. In the Castolon trench, we found a beer can which helped constrain the dates of deposits that were older than the deposits dated with the trees.

4.5. Aerial photograph interpretation and analysis

We stereoscopically analyzed aerial photographs of each study reach (Table 1). We scanned one photo of each stereo pair and used a 3rd order polynomial correction model to geo-reference each of the scanned photographs to the 2004 DOQQs. We geo-referenced 37 images. The number of ground control points used to geo-reference each image varied between 5 and 64, but most photos had more than 10 and many photos had more than 20. The root mean square errors (RMSEs) were less than 1 m for all 1980s, 1991, and 1996 photo corrections, less than 2 m for the 1968 and 1950s photo corrections, 3 m for the 1941 photo corrections, and 4 m for the 1948 photo corrections. The larger RMSEs for the older photographs reflect smaller scale and poor quality.

Table 2
Hydrologic characteristics at the Rio Grande below Rio Conchos and Johnson Ranch gages.

Gage	Flood of record[a]-Date	Long-term ave flood[a,b]	Long-term mean flow[a,c]	1901-1944(BRC), 1936-1944(JR)			1945-1985			1986-1992			1993-2008		
				Ave flood[a,b]	Mean flow[a,c]	Ave dur >438 m^3/s[d]	Ave flood[a,b]	Mean flow[a,c]	Ave dur >438 m^3/s[d]	Ave flood[a,b]	Mean flow[a,c]	Ave dur >438 m^3/s[d]	Ave flood[a,b]	Mean flow[a,c]	Ave dur >438 m^3/s[d]
Below Rio Conchos (BRC)	4220-9/4/04	464 (1901-2008)	39.3 (1901-2008)	833	64.0	3006	308	27.5	907	470	62.8	4499	240	17.4	1621
Johnson Ranch (JR)	1850–10/1/78	438 (1936–2008)	35.0 (1936–2008)	823	66.9	6969	368	27.5	1044	1044	63.0	3814	347	20.1	1899

[a] Measurement in cubic meters per second.
[b] Ave flood = Average annual flood.
[c] Mean flow = Mean annual flow.
[d] Ave dur >438 m^3/s = Average duration that the long-term average flood at Johnson Ranch (438 m^3/s) is exceeded, in m^3/s days.

We identified the boundaries of the active channel on each photo series. We distinguished between the active channel and floodplain by noting differences in elevation of geomorphic surfaces above the river and the relative abundance of vegetation on near-channel deposits. We classified surfaces with abundant, mature vegetation as floodplains, and classified most of the bare alluvial surfaces as within the active channel.

In many of the historic aerial photographs, delineating the active channel was difficult. Dense stands of vegetation were not always present along the channel margins, and a number of bare alluvial surfaces occurred at different elevations above the river. These characteristics suggest that a wide range of flood discharges and frequencies remove vegetation or prevent vegetation establishment on various geomorphic surfaces. Thus, no clear relationship existed between elevation and vegetation density discernable on many of the aerial photographs.

Significant uncertainty occurred in defining the active channel in some years of aerial photography based on the difficulties described above. In cases where photographs were taken only a few years after a large flood, many patches of bare sediment existed far from the edge of the water and the topography of near-channel areas was complex. In these photograph series, we accounted for this uncertainty by defining lines that (a) bound the largest possible area that might be considered the active channel (maximum), (b) bound the area that unquestionably would be within the active channel (minimum), and (c) bound our best estimate of the active channel at the time of the photograph. The mapping criteria that defined (a), included the extent of all bare alluvial surfaces. The mapping criteria that defined (b) included the extent of low flow channel bars or consisted of the first distinct topographic break in slope between the low flow channel and adjacent surfaces. The mapping criteria that defined (c) consisted of the distinct increase in vegetation nearest to the low flow channel, or, if vegetation was absent, consisted of a similar boundary to the minimum estimate (b). Delineation of the active channel boundary on aerial photographs taken more than a decade after large floods was straightforward, because dense riparian vegetation typically had invaded the alluvial valley to the edge of the single-thread channel. Thus, we defined the active channel as the topographic break in slope between the low flow channel and the surfaces covered by dense riparian vegetation. The minimum extent of the active channel likely includes surfaces inundated every 1-2 years, and the best estimate of the active channel is most likely overtopped by floods every 2 to 5 years. The maximum extent of the active channel is most likely inundated by large floods of a recurrence greater than 5 years. We divided the area of the active channel by the length of the channel centerline to estimate the minimum, maximum, and best estimate reach-average active channel width.

To clarify the role that vegetation invasion had in causing recent change, we calculated the percentage of the active channel bars present in 1996 that were covered by vegetation in 2004. This was not possible for earlier photographs, because high discharges at the time of earlier photographs obscured some of the active channel deposits. We estimated error for this metric in a similar manner to our active channel delineation by estimating the minimum and maximum areas of the active channel bars.

5. Results

5.1. Hydrologic changes

Total flow declined during the 20th century, although this trend was interrupted by large runoff in the late 1980s and early 1990s (Fig. 4a). The mean annual flow of the lower Rio Grande at BRC was 39.3 m^3/s for 91 years of measurements between 1901 and 2008. The mean annual flow between 1901 and 1944 at BRC, however, was 64.0 m^3/s, and was 28.8 m^3/s between 1945 and 2008. The only period of sustained large total runoff after 1945 was between 1986 and 1992 when mean annual runoff was 62.8 m^3/s. Unusually low flows occurred between 1993 and 2008 when mean annual flow was 17.4 m^3/s (Table 2).

Flood flows have similarly declined. The average annual flood at BRC between 1901 and 2008 is 464 m^3/s, but the average between 1901 and 1944 was nearly 80% larger — 833 m^3/s. The four largest floods of record and 14 of the 20 largest floods of record occurred during this period. The only subsequent period when large floods occurred in succession was in 1990 and 1991. The 1978 flood was the fifth largest of record; large floods also occurred in 1958 and 2008. The 2008 flood occurred after our field work concluded, thus, we do not explicitly evaluate its effects in this paper although we speculate on the geomorphic effects in Section 6.

The temporal pattern of high and low flow periods is the same at BRC and Johnson Ranch, because the Rio Conchos is the primary source of stream flow. The mean annual flow and average annual flood at Johnson Ranch, however, is 7%, and 18% larger, respectively, than at BRC for the period of overlapping record (1936–2008). Inflow from ephemeral tributaries downstream from Presidio (Table 2, Fig. 4a and

Table 3
Changes in channel width based on historic oblique photograph comparison.

Photo location	2004 width (m)	1901 width (m)	% Reduction
Hot Springs Canyon 1[a]	50.7	103.9	51.2
Hot Springs Canyon 2[b]	39.4	81.8	51.8
Photo location	**2004 width (m)**	**1945 width (m)**	**% Reduction**
Mouth of Hot Springs Canyon[c]	51.0	88.3	42.2

[a] Hot Springs Canyon 1 was calculated using the historic photo from Fig. 5.
[b] Hot Springs Canyon 2 is part of the larger historic photo data set and was not included as a figure.
[c] Mouth of Hot Springs Canyon was calculated using the historic photo from Fig. 6.

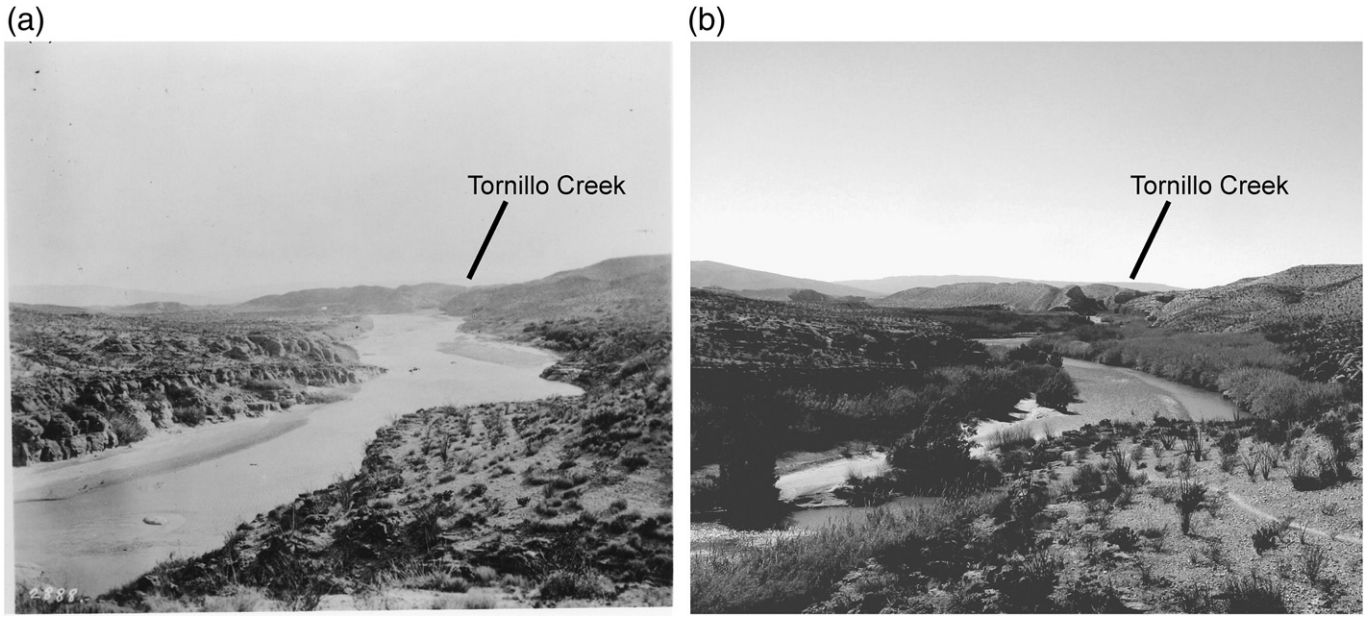

Fig. 5. Historical oblique photo pair in Hot Springs Canyon looking upstream toward Tornillo Creek. (a) Photograph taken in 1901 by the Bailey-Oberholser field investigations of the Big Bend for the United States Biological Survey. (b) Photograph taken on 3/4/08. Historic photo shows that the active channel spans the entire canyon width and contains alternate channel bars. Photo (b) shows significant accumulation of gravel, and fine sediment deposited on top of gravel which is stabilized by a thick growth of giant cane and tamarisk. The river has been converted from a river with bedrock channel banks to an alluvial river. The active channel width in photo (b) is 51% narrower than the historic 1901 photo.

b) can significantly contribute to the magnitude of floods at Johnson Ranch. For example, the 1990 flood at Johnson Ranch was 80% larger than at BRC because of inflow from ephemeral tributaries, and more than 60% larger at Johnson Ranch in 1986 and 2004. Increases in the average annual flood from tributary runoff are shown by the 10-yr running average in Fig. 4b.

A distinct difference in flood duration is associated with floods greater and less than 1000 m^3/s. The long term average annual flood at Johnson Ranch (438 m^3/s) was frequently exceeded prior to 1944, and the duration of floods greater than 1000 m^3/s often exceeded 15,000 m^3/s days (Fig. 4c). Floods less than 1000 m^3/s usually occurred for less than 5000 m^3/s days (Fig. 4c). Thus, the duration of large floods is usually 3 times greater than that of floods less than 1000 m^3/s. A 5-year running average of flood duration shows that with the exception of the large floods in 1958, 1978, and 1990/1991, floods in excess of the average annual flood have only occurred for extremely short durations since 1944.

5.2. Summary of geomorphic changes: 1900–2008

Repeated photographs spanning the entire 20th century illustrate the magnitude of channel change that has occurred in the Big Bend region. These photo comparisons provide some of the motivation for restoration efforts in the region, because the evidence of channel change is so dramatic.

The channel in Hot Springs Canyon is approximately 50% narrower than it was a century ago based on photograph comparisons from 1901 to 2004 (Table 3). In 1901, the average channel width was 82 m in one oblique photo (Fig. 5a) and 103 m in another, and the active channel spanned the entire width of the canyon. The active channel width

Table 4
Summary of oblique historical photograph data.

Photo location	Number of photos replicated	Geomorphic classification[a]	Channel narrowing[b]	Significant accumulations of gravel[b]	Significant increase in vegetative cover[b]	Vegetation type (T, C, M)[c]	Photos showing bed aggradation/degradation
Santa Elena Canyon/Terlingua Creek	8	4 Bedrock canyon 4 Alluvial	3/3	4/8	4/8	4T	4 Agg
Old River Road	3	3 Alluvial	3/3	ND[c]	3/3	3T/C/M	ND[d]
River Road	4	4 Alluvial 1 Alluvial	4/4	ND[c]	4/4	4T/C/M	ND[d]
Johnson Ranch	1	Canyon 7 Alluvial	1/1	0/1	1/1	1T/C	ND[d]
Hot Springs Canyon	9	Canyon 2 Alluvial	8/8	8/9	8/9	7T/C, 1T/C/M	ND[d]
Mouth of Boquillas Canyon	2	2 Alluvial	2/2	0/2	2/2	Native/Treatment Bar[e]	ND[d]

[a] Bedrock canyons = canyons where the channel banks are bedrock, alluvial canyon = canyons where channel banks are alluvium, alluvial = unconfined alluvial reaches.
[b] The number of photographs that show indicated change/the number of photographs that have the indicated feature as a subject (Grams and Schmidt, 2002).
[c] T = Tamarisk, C = Giant Cane, M = Mesquite (*Prosopis* spp.).
[d] ND = Not Determined.
[e] Native/treatment bar indicates that the increased vegetation is predominantly native due to NPS restoration treatments at that location.

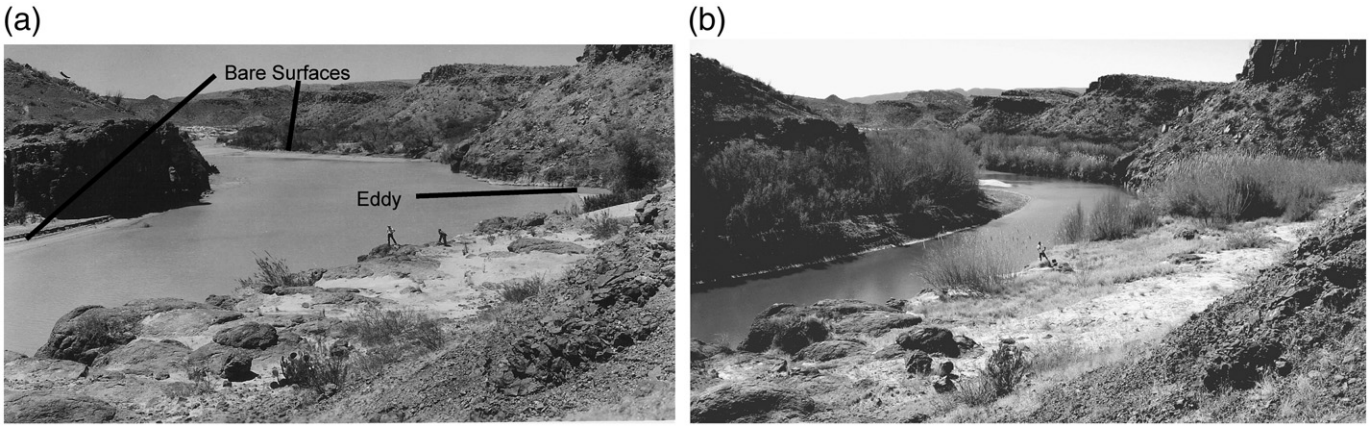

Fig. 6. Historical oblique photo pair looking upstream from the Johnson Ranch stream gage. (a) Photograph taken by unknown photographer in 1945. (b) Photograph taken on 2/23/08. Humans are present in the center of both photos for scale. 1945 photo depicts the river channel spanning the entire width of the bedrock walls. Bare sandy alternate bars are seen in the center background and in the left foreground. An eddy is present in the right mid-ground. 2008 photo depicts a floodplain surface inset within the bedrock walls with steep, high banks which are completely colonized by tamarisk. The eddy in the right foreground has filled with sediment and is colonized by giant cane.

measured from the 2004 DOQQ was 39 m (Fig. 5b) and 51 m, respectively, and the banks of the channel are now vegetated floodplains (Fig. 5b).

Generally, the repeated photographs show reductions in channel width, increases in riparian vegetation predominantly by tamarisk and giant cane, accumulation of gravel within the channel, and in a few cases, aggradation of the channel bed (Table 4). Channel narrowing and increases in riparian vegetation have occurred in all but the narrowest canyons (Table 4, Figs. 5–8). Gravel accumulation has occurred within canyons especially downstream from tributaries (Fig. 5). In many canyons, fine sediment has been deposited on top of gravel bars and has subsequently been overgrown by dense stands of riparian vegetation. Narrowing has converted some bedrock canyon reaches into alluvial canyon reaches, because the channel banks no longer encounter bedrock (Figs. 5 and 6).

In the alluvial reaches, inset floodplains now exist within the historic active channel (Fig. 7). These floodplains are overgrown by tamarisk and giant cane, and upland xeric species now grow on the abandoned banks of the former channel. In many alluvial reaches, narrowing has been so dramatic that the once wide sandy channel and low elevation floodplains, visible in the old photographs, are now completely obscured by dense vegetation (Fig. 8).

The photograph comparisons demonstrate the magnitude of century-scale geomorphic change, however, the channel change shown in Figs. 5–8 has not occurred at a constant rate. Instead, the history of channel change can be divided into three periods: (1) the period prior to 1944 when the wide, sandy, active channel bed was maintained by large floods, (2) a subsequent period of progressive narrowing between 1945 and 1992 interrupted by occasional large, long duration floods that re-widened the channel, and (3) a period of rapid channel narrowing and non-native vegetation invasion since 1992. We describe these periods below.

5.3. 1900–1944: channel maintenance

No evidence exists that the channel narrowed between 1900 and 1944. Historic oblique and aerial photographs taken between 1901 and 1941 depict a wide, sandy channel, with low elevation floodplains and sparse annual vegetation (Figs. 5a, 6a, 7a, and 8a). Active channel width, calculated from the first aerial photographs in 1941 and an oblique photograph from 1945, ranged between 88 and 102 m

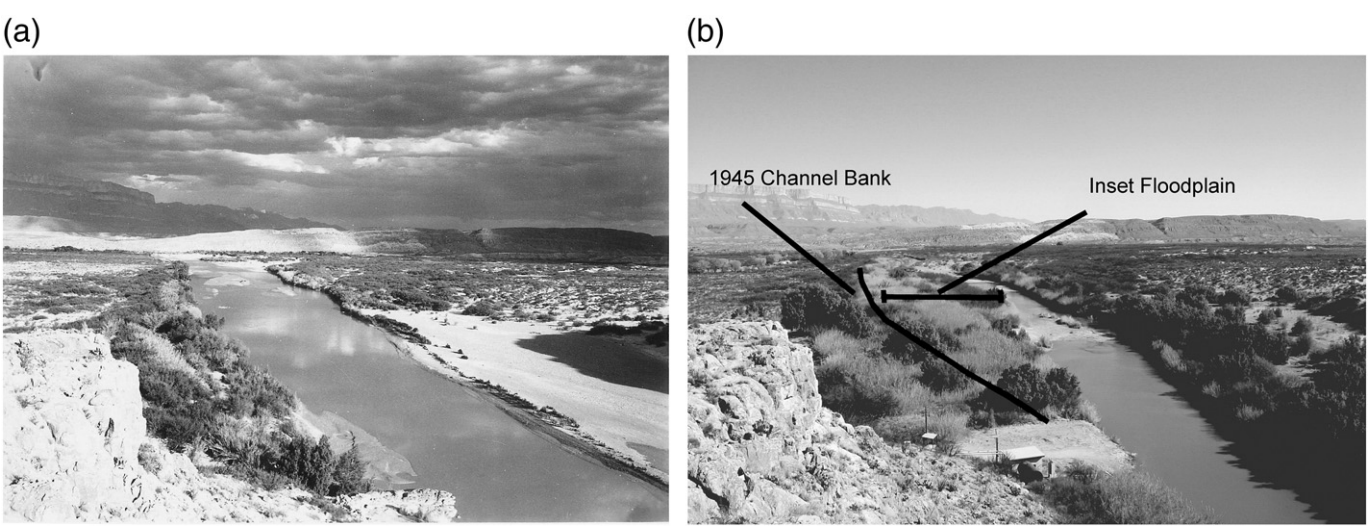

Fig. 7. Historical oblique photo pair looking downstream from the outlet of Hot Springs Canyon. (a) Photograph taken by unknown photographer in 1945. (b) Photograph taken on 2/12/08. 1945 photo shows a large bare sand bar on river right and a left bank with woody vegetation. Photo (b) shows the large bare sandbar present in photo (a) overgrown with tamarisk and giant cane. On river left, the historic channel bank can be seen in photo (b) by the break in vegetation where a thick growth of giant cane is inset into a terrace containing creosote and 4 large tamarisk. The active channel width in (b) is approximately 42% narrower than the historic 1945 photo.

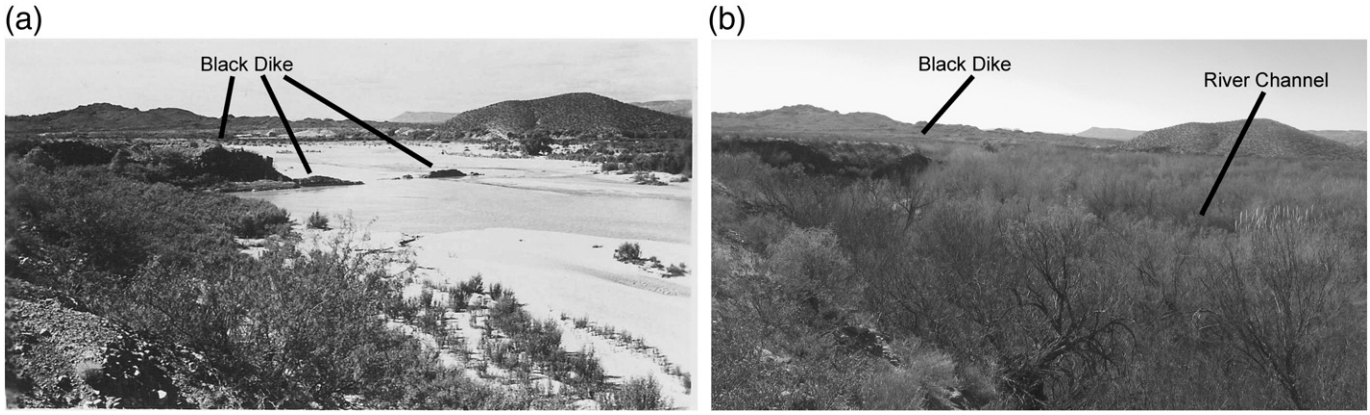

Fig. 8. Historical oblique photo pair looking downstream toward Black Dike. (a) Photograph taken by unknown photographer in 1937. (b) Photograph taken on 2/23/08. 1937 photo depicts the river flowing over and around outcrops of the dike with large bare channel margin bars colonized by a few annual plants. 2008 photo shows that view of the black dike is nearly entirely obscured by tamarisk. Smaller amounts of giant cane are growing on the channel margins. Fine sediment has accreted on the downstream portion of the dike outcrops and is stabilized by thick growths of tamarisk. River in 2008 flows to the right of all dike outcrops.

(Tables 3 and 5, Fig. 7) which is similar to the values obtained from the oblique photographs taken in 1901 (see Section 5.2). In many places, the river was multi-threaded and flowed around numerous, large, bare, active channel bars (Figs. 5, 8, and 9). Thus, the frequent large floods and large total stream flow during this period, maintained the large channel size depicted in these photographs, and helped to prevent progressive infilling of the channel and encroachment of vegetation.

5.4. 1944–1992: narrowing and resetting

Channel narrowing began in the mid-1940s, however, narrowing was interrupted by occasional large floods that re-widened the channel. Aerial photographs taken in 1969 show that the channel was 27 to 30% narrower than depicted in photographs from 1941 (Table 5, Figs. 9 and 10). Nearly all bare active channel deposits present in the 1940s photographs had been overgrown by vegetation by 1968, and nearly all secondary channels were abandoned (Fig. 9). Narrowing and vegetation establishment resulted in the conversion of the river from a multi-thread to a single thread during these years. A large flood of 1520 m^3/s occurred in 1958. Although no data are available to characterize the degree to which this flood widened the channel, we believe this must have occurred and explain our logic in Section 6.

Discharge measurements show that channel narrowing was reversed in the fall of 1978 by a large, long duration flood (1,850 m^3/s, >13,700 m^3/s days) that widened the channel (Fig. 11a and b). The evidence of channel widening is the upward shifts of the at-a-station hydraulic geometry curves for width and cross-section area. This event was the flood of record at Johnson Ranch and widened the channel by 10 m and increased channel cross-section area by approximately 50%. Aerial photographs taken in the mid-1980s also show that in some localized areas, riparian vegetation was absent from areas that had been densely vegetated in 1968 (Fig. 9), indicating that vegetation was stripped by the 1978 flood. Following the 1978 flood, channel narrowing resumed. Cross-section measurements at the Johnson Ranch gage show that within 7 years after the flood, the channel had narrowed by approximately 10 m or 15% (Fig. 12a). Narrowing between 1978 and 1990 occurred at rate between 0.45 m/yr and 1.42 m/yr, respectively, based on hydraulic geometry relations and cross-section measurements at the gage.

Narrowing was again reversed by a flood with a peak of 1410 m^3/s (>17,500 m^3/s days) in fall 1990, and another flood of 1030 m^3/s (>17,600 m^3/s days) in fall 1991. Aerial photographs indicate that these floods widened the channel by as much as 35% (Table 5, Figs. 9 and 10). Bank erosion was widespread, and in some areas, large bars were created (Fig. 9). Discharge measurement notes at the Johnson Ranch gage show that the channel widened by 8 m (Figs. 11c, 12a)

Table 5
Active channel width of Rio Grande for Castolon, Johnson Ranch, and Boquillas reaches.

Reach	Flight date	Active channel width (m) best estimate	Active channel width (m) minimum	Active channel width (m) maximum	Minimum error (m)	Maximum error (m)	% Change from previous photo based on best estimate
Castolon	1941	102	101	122	1	20	
	1948	99	95	118	4	20	−3
	1968	74	72	75	2	0	−25
	1986	68	65	79	3	11	−9
	1991	90	86	101	4	11	33
	1996	68	66	95	2	27	−24
	2004	44	43	44	1	1	−36
Johnson Ranch	1941	88	88	99	0	12	
	1948	78	78	97	0	19	−10
	1968	62	60	62	2	0	−21
	1984	62	60	65	1	3	0
	1991	83	74	83	9	0	35
	1996	76	72	84	3	9	−9
	2004	43	43	44	0	0	−43
Boquillas	1959	72	65	78	7	5	
	1984	70	68	86	3	16	−3
	1991	74	69	83	6	9	5
	1996	52	51	82	1	30	−30
	2004	48	47	50	1	2	−9

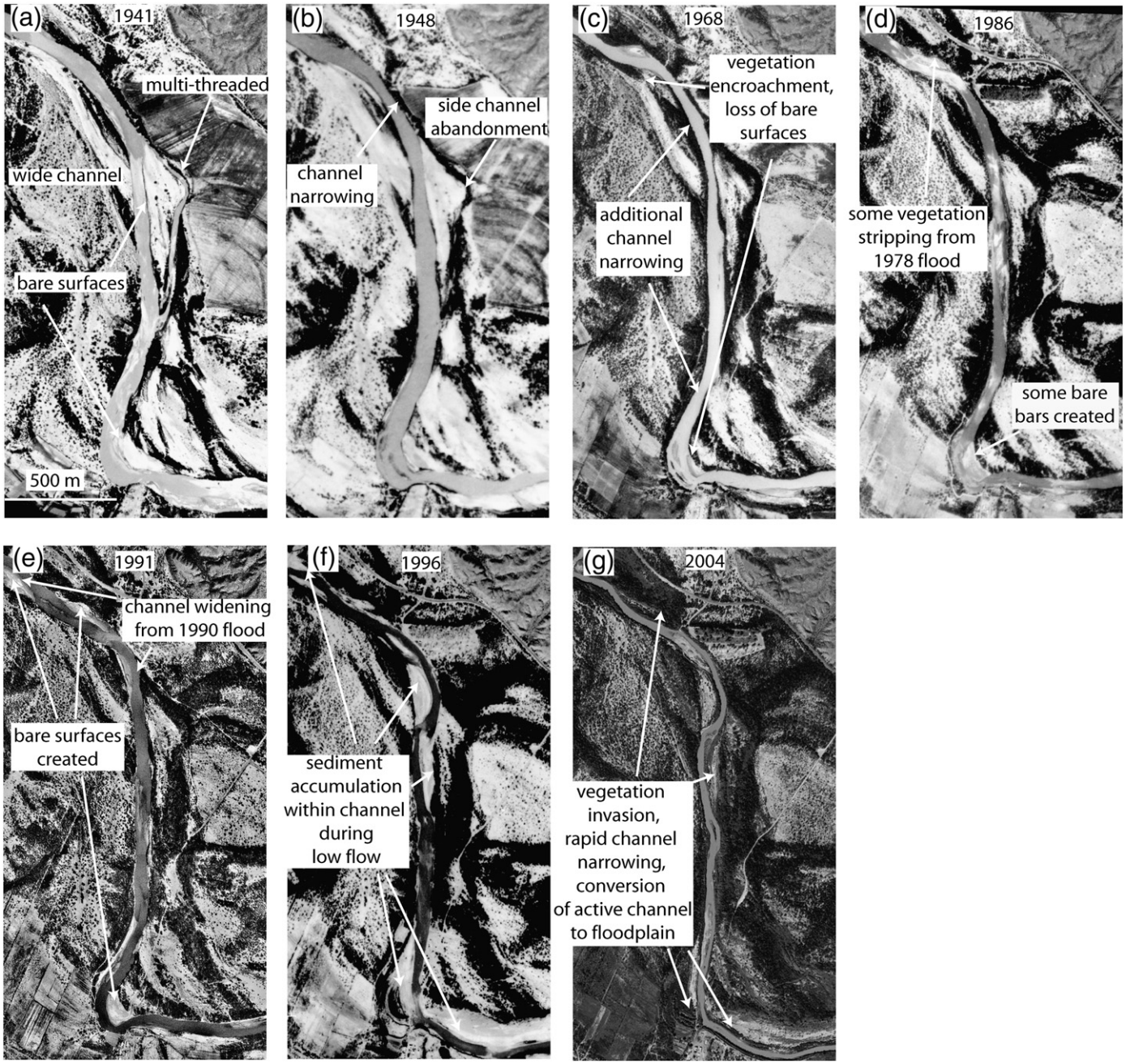

Fig. 9. Aerial photographs within the Castolon reach. Photos depict the abandonment of a side channel in 1941 (a), and vegetation colonization and channel narrowing between 1941 and 1986 (a-d). Channel widening occurred in 1978, and most likely in 1958, however, temporal resolution of aerial photographs do not depict the changes. Photograph (e) depicts channel widening due to 1990 flood and the creation of bare surfaces. Sediment accumulated within the channel by 1996 (f), and vegetation colonized nearly all bare surfaces by 2004 (g).

and that the channel bed was scoured by 3 m at the gaging cross-section (Fig. 12a). Although large floods caused significant channel widening, these floods did not return the channel to its width observed between 1901 and 1944.

5.5. 1993–2008: rapid channel narrowing and vertical floodplain accretion

Channel narrowing resumed during the low-flow years between 1993 and 2008. Discharge measurement notes at the Johnson Ranch gage show that the bed scour caused by the 1990/1991 floods had entirely filled in by June 1992 (Fig. 12b). By 2002, the channel had narrowed by approximately 20% through the development of an inset floodplain (Fig. 12b), and by 2005, approximately 1 m of additional vertical accretion had occurred on the floodplain (Fig. 12b). Between the 1991 flood and 2006, channel cross-section area decreased by approximately 30% at the Johnson Ranch gage. Aerial photograph analyses show that the reductions in channel width observed at the gage were typical of the entire study area. Active channel width in all three reaches declined by 36 to 52% between 1991 and 2004 (Figs. 9 and 10). Narrowing occurred at a rate of 3.53, 3.07, and 1.85 m/yr in the Castolon, Johnson Ranch, and Boquillas reaches, respectively (Fig. 10), which is approximately twice as fast as observed between 1979 and 1990.

Stratigraphic analyses of the two trenches demonstrate that channel narrowing occurred by vertical accretion of fine grained sediment on top of sand and gravel bars between 1993 and 2008. (Fig. 13). Today, vertically accreted deposits are inset within natural, sandy levees that were the channel banks after the recession of the

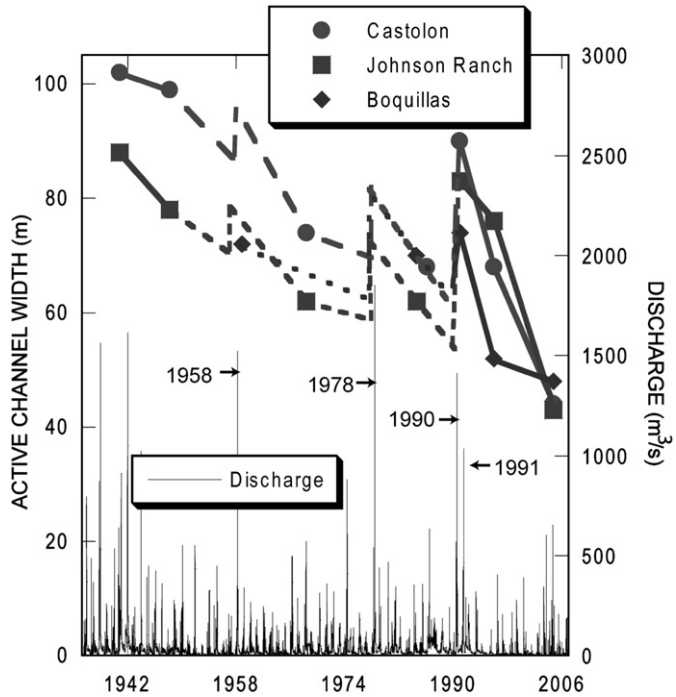

Fig. 10. Active channel width at the Castolon, Johnson Ranch, and Boquillas reaches determined from aerial photographs. Solid data points are measured channel widths. Solid lines depict trends of change, and dashed lines are inferred trends in channel width based on measured discharge data at the Johnson Ranch gage. Widening occurred in 1978 at Johnson Ranch; however, the poor temporal resolution of the aerial photographs was insufficient to determine the magnitude of reach-averaged widening. Widening from the 1958 flood is inferred based on observations of widening from floods in 1978 and 1990/1991 which were of similar magnitudes. Note that the floods of 1990/1991 did not completely re-widen the channel to widths measured in the 1940s, thus, even though occasional widening has occurred, progressive narrowing has been the dominant trend.

1990/1991 floods. Tamarisk germinated at the base of the trenches near the top of the buried sand and gravel bars. Ages, burial depths, and internal ring anatomy of tamarisk and willows removed from the trenches show that between 2.75 and 3.5 m of vertical accretion occurred since 1993. The rate of vertical accretion was 0.22 and 0.17 m/yr at the Castolon and Boquillas trench sites, respectively. Since 1993, the channel at the Castolon and Boquillas trench sites has narrowed by 55 and 33%, respectively, 83 and 90% of which was observed in the trenches. Giant cane has colonized the sandy levees as well as the current channel banks, and thick groves of tamarisk exist onshore of the channel banks. We observed an abundance of buried cane within the bank of the channel in the Castolon trench reflecting such rapid accretion of the floodplain that nearly 2 m of buried cane had not yet decomposed.

The recent aerial photographs, and trench data show that vegetation promoted the conversion of active channel surfaces to floodplains. As observed in the trenches, tamarisk established within the active channel during the low flow years after 1992. Sediment deposited among established vegetation was stable because erosional contacts were only occasionally observed in the stratigraphy. No buried cutbanks existed except the few created by the channel widening floods, and scour pits and large-scale erosion features were few. Aerial photographs show that substantial accumulation of sediment occurred within the channel between 1991 and 1996 at the same time much of the tamarisk germinated (Fig. 9). Buried decomposing plants were numerous, as well as vegetation induced sedimentary structures (Rygel et al, 2004) indicating that vegetation establishment precluded much of the sediment accretion. Vegetation colonized 77, 89, and 39% of the active channel surfaces in the Castolon, Johnson Ranch, and Boquillas reaches, respectively, by 2004, which effectively converted them to floodplains (Table 6).

Channel narrowing and floodplain accretion resulted in increases in river stage, and a decreased discharge required for floodplain inundation. Increases in river stage were observed after 2000 at the Johnson Ranch gage and the Castolon stage plate (Fig. 14). These shifts affected stages of discharges greater than approximately 100 m^3/s. After 2000, stages occurred approximately 1 to 2 m higher for the same discharge compared to the 1990s. Dense stands of giant cane, growing on the banks just above the base-flow stage, may also be partially responsible for this increase in stage by reducing flow velocities along the channel margin, however, we have no measurements that show this. These increases in stage resulted in flooding at lower discharges. Flooding in the 1990s occurred during discharges greater than approximately 400 m^3/s, and in the 2000s occurred during discharges of approximately 200 m^3/s (Fig. 11e). This is illustrated by the distinct break in slope in the hydraulic geometry relation for width (Fig. 11e), because width increases rapidly as flows overtop the channel banks.

The changes observed between 1993 and 2008 reflect similar changes that Everitt (1993) identifies on the Rio Grande upstream from the Rio Conchos. Reductions in discharge led to channel narrowing which was temporarily reversed by large flows in 1942. Narrowing resumed after 1942, and resulted in the subsequent loss of channel capacity, increases in stage, and continued floodplain accretion even though flood flows were reduced. Unlike Everitt (1993), we demonstrate that vegetation establishment exacerbated the rate and magnitude of channel narrowing and floodplain accretion. Based on data reported by Everitt (1993), we calculated that narrowing upstream of the Rio Conchos occurred at a rate between 0.5 and 1 m/yr. Narrowing in the Big Bend region, however, occurred at a rate between 1.85 and 3.53 m/yr between 1993 and 2008. Thus, even though hydrologic and geomorphic change has been similar, the rate of recent narrowing on the lower Rio Grande has been faster because of the effects of vegetation.

5.6. Additional results and analysis

Large floods in the 1940s, 1978, and 1990/1991 created a wide heterogeneous channel and floodplain. These floods scoured vegetation, eroded channel banks, and created large sediment deposits along the channel margins. The active channel was thus difficult to delineate on aerial photographs taken soon after these floods. On the 1940s and 1990s aerial photographs, the difference between the minimum and maximum active channel width was between 10 and 20 m within a reach (Table 5). Conversely, when more than a decade elapsed between large floods and aerial photograph collection, such as in 1968 and 2004, channel narrowing had occurred, vegetation had established on bare surfaces, and active channel delineation was simple. For these photographs, the difference between the minimum and maximum boundaries of the active channel was less than 3 m. This indicates that large floods create laterally heterogeneous channels, whereas channel narrowing during low-flow periods results in channel simplification.

Large floods also create longitudinal heterogeneity. The 2004 aerial photograph analyses show that the width of the active channel for all three study reaches converged to a common width between 43 and 48 m (Fig. 10). This contrasts with measurements of the channel from the 1940s and 1950s. During these periods, the difference in the width of the active channel between each reach was at times greater than 20 m (Table 5). This indicates that as channel narrowing occurs, unique characteristics of each reach, such as geologic confinement or tributary effects are lost. The above analyses indicate that heterogeneity, and our ability to measure geomorphic attributes on this river, varies according to the recent flood history, and the associated channel width.

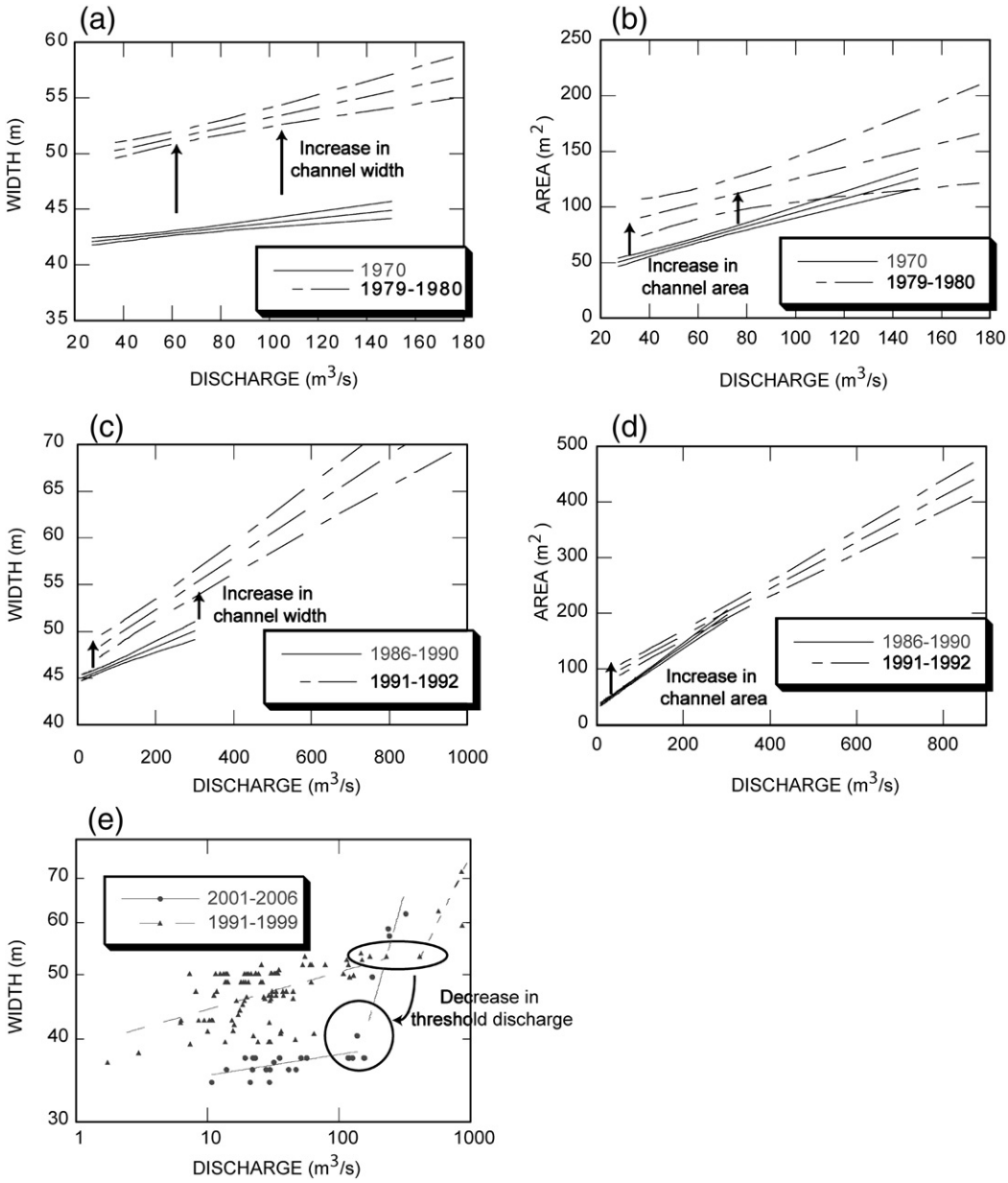

Fig. 11. Hydraulic geometry relations at the Johnson Ranch gage. The 1970 data represent the oldest notes of measured discharge obtained. Data from measurements between 1970 and 1979 could not be located by the IBWC. Erosion and channel widening from large floods are depicted by the increases in channel width and cross section area in 1979 (a, b) and 1991 (c, d). Channel narrowing and loss of channel cross-section area during the 1990's and 2000's resulted in a reduction in the discharge for over-bank flow from approximately 400 m^3/s in the 1990s to approximately 200 m^3/s after 2000 (e). Channel widths for over-bank flows are depicted by the steep increase at these respective discharges. Error envelopes for width and area data represent the 95% confidence interval about the regression lines.

5.7. Floods and geomorphic process

Comparison of the historical records of flooding and geomorphic change suggest that two types of floods occur on the lower Rio Grande. Small to moderate magnitude floods (<1000 m^3/s) typically occur for short durations (<5000 m^3/s days), and are depositional events that contribute to channel narrowing and vertical floodplain accretion. Floods greater than 1000 m^3/s, such as those that occurred in 1978, 1990, and 1991, caused channel bank erosion and channel widening. We believe that the 1958 flood was also a widening flood, however, data are insufficient to determine this. We refer to these channel widening floods as channel reset events, because they temporarily reset the channel geometry to a previous, wider state by eroding channel banks, stripping vegetation, and re-creating large active channel bars. These channel resetting floods are similar to Nanson's (1986) "catastrophic floodplain stripping" and Griffin and Smith's (2004) "floodplain unraveling" processes.

Prior to 1944, these large magnitude, long duration floods were common and the channel was wide, sandy, and multi-threaded. With the exception of the 1944 flood, the six floods in excess of 1000 m^3/s prior to 1944 all occurred for durations that exceeded 10,000 m^3/s days and most exceeded 15,000 m^3/s days. Since 1944, however, only four floods in excess of 1000 m^3/s occurred (Fig. 15), the channel has narrowed, vegetation has invaded, and heterogeneity has been lost. Although channel resetting has occurred, the resets have been incomplete because they have never returned the river to its width prior to 1944 (Fig. 10). Thus, the decline of large, long duration, erosive floods has resulted in the formation of the narrow, vegetated channel that existed in fall 2008.

We summarize the above processes with a general model depicting cross-sectional change during episodes of narrowing and

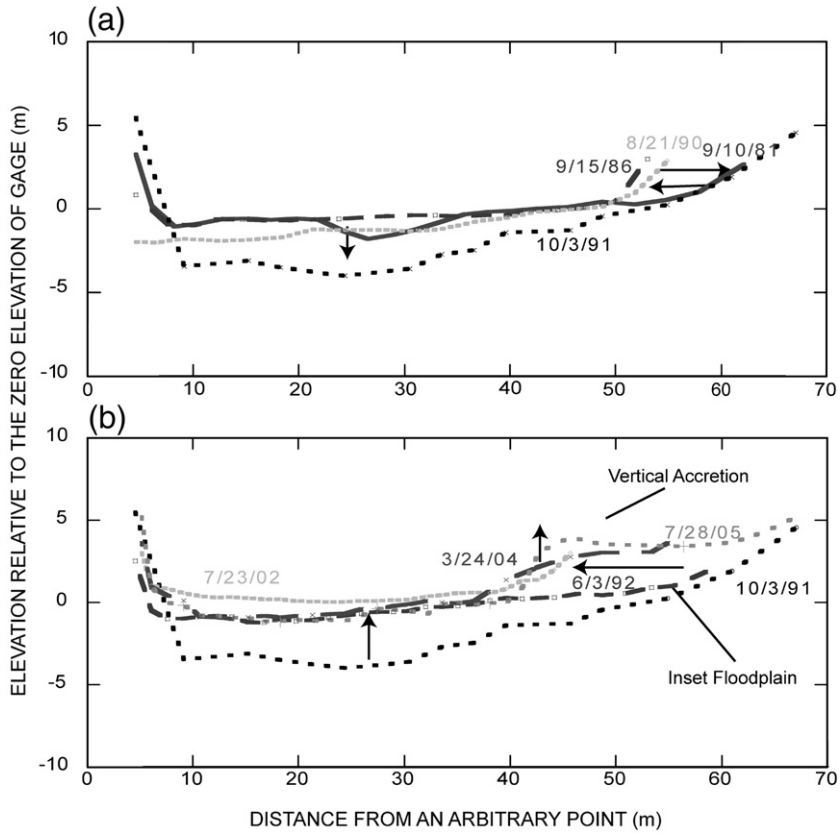

Fig. 12. Channel cross-sections measured at the Johnson Ranch cableway. (a) Cross–sections measured from 1981 to 1991. These measurements indicate up to 7 m of channel narrowing occurred between 1981 and 1990. Large floods in 1990 and 1991 re-widened the channel approximately 10 m and scoured the channel bed approximately 3 m. (b) Cross-sections measured from 1991 to 2005. Scour following the floods of 1990 and 1991 filled in by the 6/3/92. Narrowing in excess of 10 m occurred between 6/3/92 and 7/3/02. Narrowing occurred through the development of an inset floodplain. Between 7/23/02 and 7/28/05, additional narrowing as well as approximately 1 m of vertical accretion occurred.

episodes of reset (Fig. 16). A wide channel was created and maintained by frequent floods greater than 1000 m^3/s in the early 20th century (Fig. 16a). Periods of channel narrowing during low mean and peak flow between 1945 and 1990 occurred by the accumulation of sediment and the establishment of vegetation within the channel (Fig. 16b). Three channel resetting floods in excess of 1000 m^3/s temporarily widened the channel in 1978, 1990, and 1991 (Fig. 16c). Rapid channel narrowing followed the resetting floods of 1990 and 1991, during years of extremely low stream flow. Narrowing occurred through the development of vertically accreting inset floodplains on top of active channel bars. This period of narrowing was characterized by a lack of floods exceeding 1000 m^3/s as well as the invasion of non-native vegetation within the channel and the subsequent conversion of the channel to floodplain (Fig. 16d).

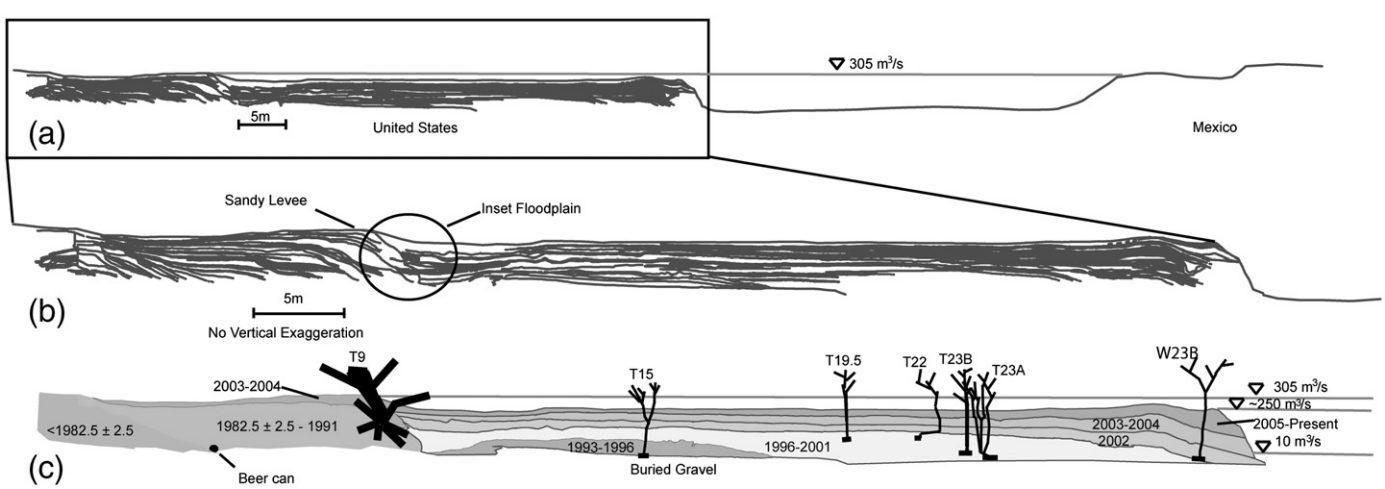

Fig. 13. Stratigraphy and burial dates observed in the Castolon trench. (a) Surveyed cross-section at the Castolon trench site upstream of Cottonwood Campground. Mapped stratigraphy of the Castolon trench is displayed on the left of the cross section. The approximate elevation of the 2-yr flood stage is also displayed. (b) Mapped stratigraphy of the Castolon trench. Stratigraphic contacts defined by unconformities and disconformities. (c) Castolon trench displaying locations of the dated tamarisk and willow (tamarisk (T), willow (W)). Approximate germination horizons are indicated in a dark black horizontal line. Dates indicate periods of sediment accretion as observed from the wood anatomy in trees. Approximate date of beer can constrains deposition for sediments deposited before 1991. Stages of the base flow (~10 m^3/s) and the approximate 2-year flood stage (305 m^3/s) are also shown.

Table 6
Percent conversion of active channel surfaces.

Reach	"Best estimate" % conversion	Minimum % conversion	Maximum % conversion
Castolon	76.5	74.1	83.1
Johnson Ranch	89.4	87.6	89.5
Boquillas	39.1	34.2	68.4

6. Discussion: feedback mechanisms

We identified negative and positive feedback mechanisms associated with geomorphic changes on the lower Rio Grande. Negative feedbacks are mechanisms of self-regulation that prevent progressive geomorphic change in one direction, and positive feedbacks are mechanisms that reinforce or exacerbate progressive change (Chorley and Kennedy, 1971). On the lower Rio Grande, negative feedbacks are the large floods that dominated the beginning of the 20th century and occasionally occurred after the 1940s. Positive feedback is the exacerbation of channel narrowing by vegetation which decreases channel capacity and maintains overbank floodplain accretion even in a declined flood regime.

Positive feedbacks dominated the low flow period between 1993 and 2008. Sediment accumulated and vegetation established within the channel during this period. Tamarisk germinated on top of active channel bars and were subsequently buried by 2.75 to 3.5 m of sediment as inset floodplains formed within the previous channel margins. Nearly 2 m of buried giant cane was also observed within the floodplain trenches. Although we have no direct measurements of bank strength, floodplain flow velocities, or rates of sedimentation within and without areas of dense vegetation, vegetation establishment and vertical floodplain accretion was extremely rapid. Vegetation establishment and vertical accretion effectively converted between 39 and 90% of the active channel bars to floodplains during this period (Table 6, Fig. 9). Based on the high vegetation densities, the stabilizing effects of the roots, the fact that much of the vegetation established within the active channel, and the large amount of preserved buried vegetation, we demonstrate that vegetation actively promoted sediment deposition, channel narrowing, and vertical floodplain accretion. The positive feedbacks are well expressed in the upward shifts of the stage-discharge relations at the Johnson Ranch gage and the Castolon stage plate after 2000 (Fig. 14). These shifts show that even though the magnitude of the average annual flood was reduced by 40 to 50% compared to the previous period (Table 2), overbank flooding, vertical floodplain accretion, and channel narrowing continued to occur at rapid rates (Figs. 16d and 17).

Evidence shows that positive feedbacks must have also existed in the past. The onset of channel narrowing in the mid-1940s occurred when peak flows consisted of small magnitude, short duration, floods from ephemeral tributaries (Fig. 4). Sediment accumulated along the channel margins and dense stands of vegetation established on these bare surfaces, as shown in the aerial photographs taken in 1968 and in the 1980s during periods of narrowing. This is the same pattern of change observed after 1992. Based on the similarities of sediment accumulation and vegetation establishment, and the feedbacks we illustrated above, positive feedbacks must have also operated during earlier periods of narrowing between 1945 and 1990 (Figs. 16b and 17).

Conversely, large floods acted as negative feedbacks in 1958, 1978, 1990, and 1991. These channel resetting floods acted to regulate the geomorphic form of the river by interrupting and temporarily reversing the previous episodes of channel narrowing (Fig. 16c).

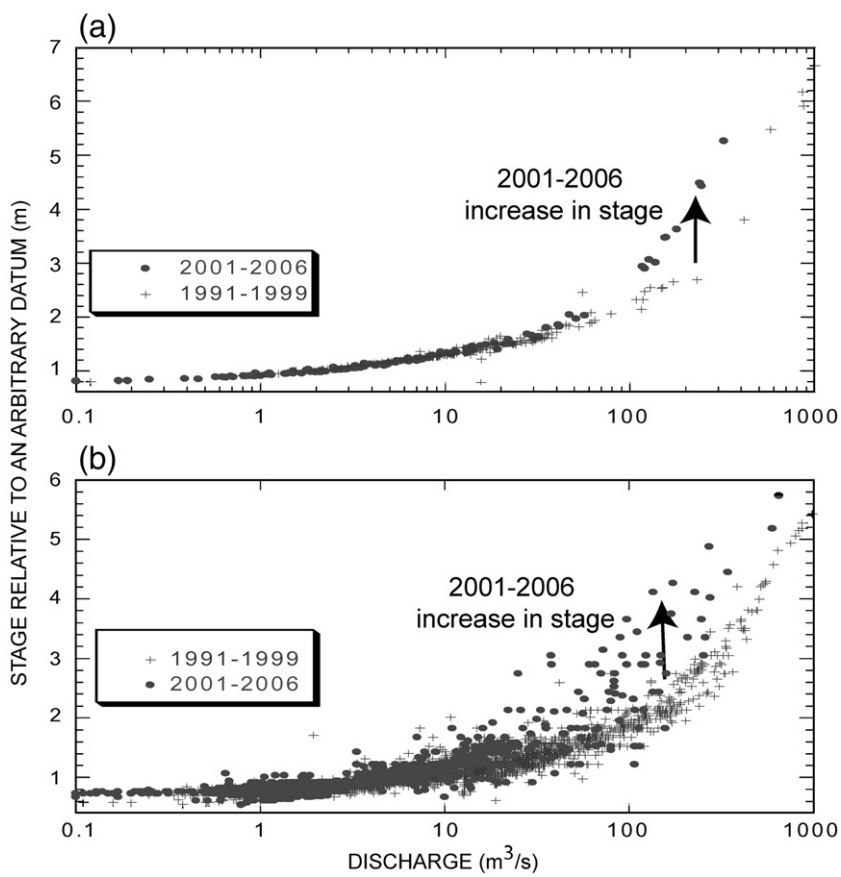

Fig. 14. Stage discharge rating relations for flows measured at (a) Johnson Ranch and (b) the Castolon stage plate. Note the increase in stage from 2001 to 2006 for discharges greater than approximately 100 m^3/s caused by reductions in channel capacity and potential velocity reductions by thick bank vegetation.

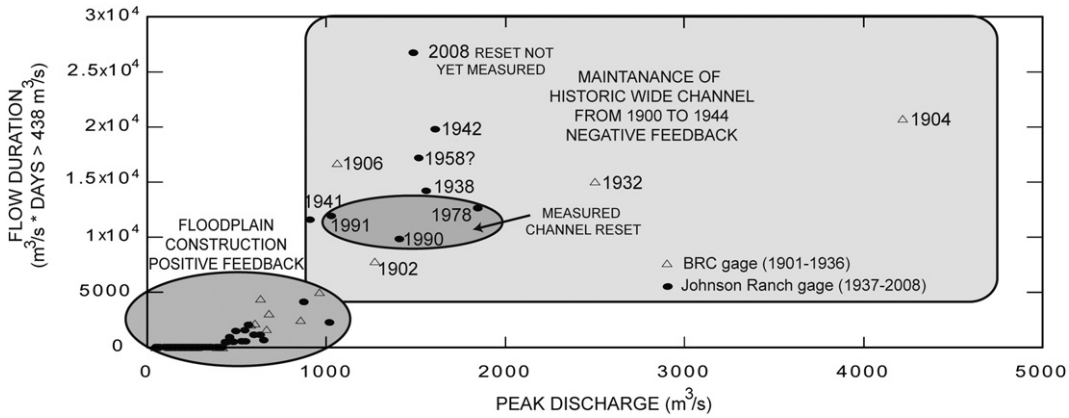

Fig. 15. Peak discharge and duration in m^3/s days greater than the average annual flood at Johnson Ranch. This plot indicates the amount of time that 438 m^3/s is exceeded annually. Floodplain construction flows and channel resetting flows determined from notes of measured discharges, dendrogeomorphic and stratigraphic analyses of inset floodplain deposits, and aerial photographs. Floods greater than 1000 m^3/s observed at the BRC gage before operation of the JR gage are also plotted. Region of inferred channel maintenance flows prior to 1944 determined from distribution of large floods. Note the frequency of floods in excess of 1000 m^3/s prior to 1944, and the few floods after 1944.

Although no aerial photographs or gage measurements bracket the 1958 flood, the magnitude and duration of this flood was as large as the other channel resetting floods (Fig. 15), and thus, we presume had the same geomorphic effect. Channel resetting floods, however, have never completely restored the channel to widths observed prior to the onset of narrowing. Thus, the magnitude of positive feedback has been greater than that of negative feedback since 1945, and the legacies of previous periods of channel narrowing have persisted (Fig. 17).

Since 1945, the interplay between positive and negative feedbacks has determined the long-term trend of channel change. This interplay includes three variables: the rate of narrowing during positive feedbacks, the magnitude of channel resetting during negative feedbacks, and the duration of time between negative feedbacks. Since 1945, the rate of narrowing has increased, the magnitude of channel reset has been less than that of channel narrowing, and large floods have only occurred every decade or two.

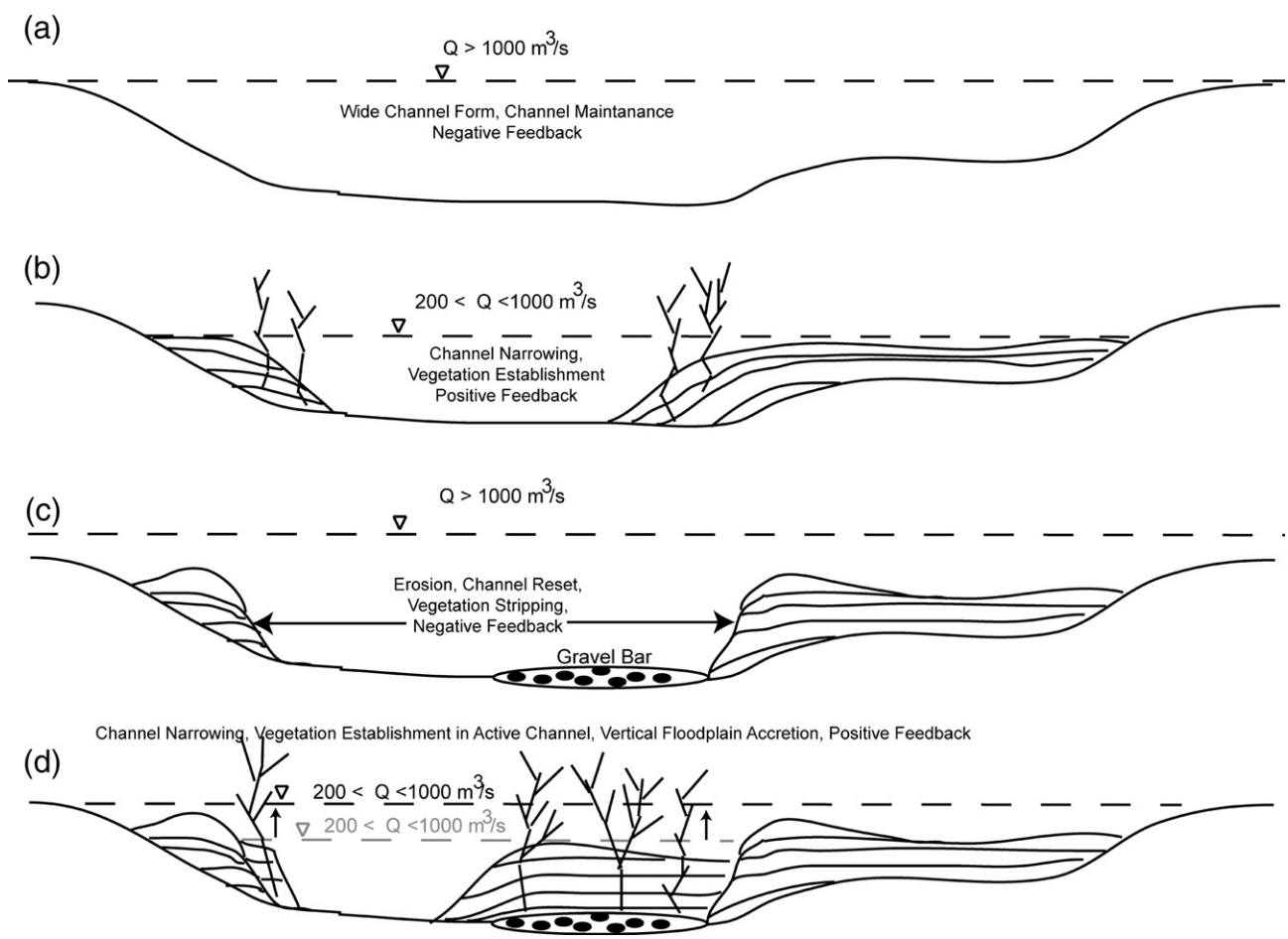

Fig. 16. General model of historic channel changes. (a) Cross-section representing channel observed in historic oblique photos between 1900 and 1944. (b) Channel narrowing as observed between the mid-1940s and the late 1978s. (c) Channel resetting flows as observed in 1979, 1990, and 1991. (d) Repeated channel narrowing after 1992. Narrowing occurs through the development of vertically accreting inset floodplains on top of active channel bars as inferred from floodplain trenches.

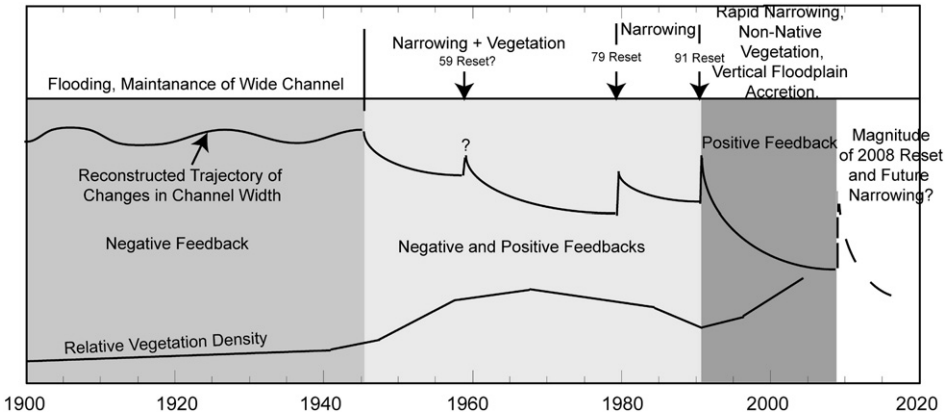

Fig. 17. Reconstructed changes in channel width, and timeline of feedback mechanisms.

The net result of these three factors has been a progressive decline in channel width.

The interaction of positive and negative feedbacks described above has created a state of disequilibrium manifested in the continuous change of channel and floodplain geometry between 1945 and 2008 (Fig. 17). Nanson and Erskine (1988) referred to this state of disequilibrium as "episodic disequilibrium", where "there is no evidence of distinct equilibrium conditions at any point, although the rate of change between each threshold is much slower than at the threshold (p. 207)." In the case of the lower Rio Grande, the threshold events are the channel reset events, with the slower processes of channel narrowing occurring during the intervening years. Nanson (1986) explicitly invoked this concept of disequilibrium on rivers in New South Wales, Australia, which described catastrophic floodplain stripping after prolonged periods of narrowing, and Pizzuto (1994) documented a similar pattern on the Powder River as the channel contracted following a large flood in 1978. These studies and others (Schumm and Lichty, 1963; Burkham, 1972; Hereford, 1984), however, describe channel contraction as a longer term process taking many decades or centuries to be fully realized. In this study, positive feedbacks have caused extremely fast rates of channel narrowing and floodplain accretion such as described after 1992.

The geomorphic form prior to 1944, however, reflects much different geomorphic processes. Floods in excess of 1000 m^3/s occurred approximately once every 4 years, frequently reworking the numerous large bars throughout the study area, and maintaining an average channel width of approximately 100 m based on historical photography (Fig. 17). Because the hydrology was dominated by frequent large floods, the geomorphic form did not appear to continually contract and reset as in the period after 1945. Instead, the river looked much the same in the early 1940s as it did at the turn of the 20th century, and no narrowing had occurred. It appears that the maintenance of channel form by the frequent large floods is more akin to a "steady-state" or "dynamic equilibrium" where oscillations about a mean occurred but progressive change in one direction did not, or was imperceptible over the time period of the study (Chorley and Kennedy, 1971; Nanson and Erskine, 1988).

The crossing of a hydrologic threshold in the mid-1940s caused the above shift in the equilibrium states. Although some flow was retained behind dams in the upper portions of the basin in the early 1900s, floods still occurred at a sufficient magnitude and frequency that negative feedbacks dominated and channel width was maintained. Additional dam construction in the late 1930s and 1940s, however, caused significant declines in stream flow, and the associated reductions allowed positive feedback mechanisms to dominate and channel narrowing to occur. Thus, although channel resetting floods can temporarily restore a wider channel, complete restoration can only occur by an increase in the frequency of large floods thereby reversing hydrologic trends back across this threshold.

We expect future channel change to occur much the same as between 1945 and 2008 for two reasons: flood flows are heavily regulated, and dense non-native vegetation is pervasive. The passage of large floods for channel maintenance purposes is socially, economically, and politically unpopular. Most rehabilitation efforts focus on the removal of non-native vegetation along the river corridor with hopes to destabilize stream banks and promote channel widening during future floods. Tal et al. (2004) described the "ratchet" effect wherein once vegetation colonizes active portions of the channel bed, it is often difficult to remove, thereby promoting the conversion of a laterally unstable, multi-thread river to that of a single thread which occurred in this study. The ratchet effect may also apply to our observations that channel width and vegetation density is negatively correlated (Fig. 17), and that the dominance of vegetation along the river corridor may limit the effectiveness of future resetting floods.

The most recent large flood occurred upon the completion of this study in September 2008. This flood occurred for the longest duration (in m^3/s days) over the entire record (Fig. 15) and was the result of a hurricane in the Rio Conchos basin. Initial observations suggest this flood considerably widened the channel, however, data are still being collected to determine the magnitude of widening and the role that vegetation played during the flood. Based on the density of vegetation present before this flood, we believe that the magnitude of reset will be less than the magnitude of narrowing since 1992 and that rapid rates of narrowing will once again ensue.

7. Conclusions

Reductions in mean and peak stream flow to the lower Rio Grande in the Big Bend region resulted in channel narrowing, vertical floodplain accretion, and establishment of non-native vegetation. The channel of the lower Rio Grande has narrowed by more than 50% since 1941. Progressive narrowing was temporarily interrupted by at least three floods in excess of 1000 m^3/s that widened the channel (1978, 1990/1991). The 1978 flood widened the channel by approximately 20%, and the 1990/1991 floods widened the channel by over 30%. Another large flood also occurred in 1958, but we were unable to determine its geomorphic effect. These large floods acted as negative feedbacks by resetting the narrowed channel to a previous, wider state.

Following the floods of 1990 and 1991, the channel has narrowed between 36 and 52%, when no flows exceeded 1000 m^3/s, and peak flows consisted of small, short duration tributary floods. In two floodplain trenches, evidence shows that 2.75 and 3.5 m of vertical accretion occurred between 1993 and 2008. Floodplains accreted at a rate of 0.16 and 0.20 m/yr. Channel narrowing and vertical accretion was exacerbated by the positive feedback of the invasion of vegetation within the channel that in some localities, converted nearly 90% of bare, active channel bars to vegetated floodplains.

Positive feedbacks during the recent period of narrowing is expressed in upward shifts in the stage discharge relation as the channel lost capacity, floodplains vertically accreted, and non-native

vegetation established. These upward shifts resulted in over-bank flooding at lower discharges and further vertical accretion. Thus, although the average annual flood between 1993 and 2008 was substantially reduced compared to the previous period, over-bank flooding and vertical accretion occurred at high rates. Overall, the changes observed on the lower Rio Grande reflect a shift in the geomorphic nature of the Rio Grande from a wide, geomorphically complex river that was created and maintained by frequent large floods prior to 1944 to a simple rectangular channel with steep definable banks and few bare active geomorphic surfaces.

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